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CK-12 Biology I

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Chapter 1

Foundations of Life Science

1.1 Lesson 1.1: Nature of Science

Lesson Objectives

- List the principles that should guide scientific research.
- Examine a scientist's view of the world.
- Outline a set of steps that might be used in the scientific method of investigating a problem.
- Explain why a control group is used in an experiment.
- Outline the role that reasoning plays in examining hypotheses.
- Examine the function of the independent variable in an experiment.
- Define what is meant by a theory and compare this to the meaning of hypothesis.

Introduction

The goal of science is to learn how nature works by observing the physical world, and to understand it through research and experimentation. Science is a distinctive way of learning about the natural world through observation, inquiry, formulating and testing hypotheses, gathering and analyzing data, and reporting and evaluating findings. We are all part of an amazing and mysterious phenomenon called "Life" that thousands of scientists everyday are trying to better explain. And it's surprisingly easy to become part of this great discovery! All you need is your natural curiosity and an understanding of how people use the process of science to learn about the world.

Goals of Science

Science involves objective, logical, and repeatable attempts to understand the principles and forces working in the natural universe. Science is from the Latin word, *scientia,* which means "knowledge." Good science is an ongoing process of testing and evaluation. One of the intended benefits for students taking a biology course is that they will become more familiar with the scientific process.

Humans are naturally interested in the world we live in. Young children constantly ask "why" questions. Science is a way to get some of those "whys" answered. When we shop for groceries, we are carrying out a kind of scientific experiment (**Figure** 11.1). If you like Brand X of salad dressing, and Brand Y is on sale, perhaps you try Brand Y. If you like Y you may buy it again even when it is not on sale. If you did not like Brand Y, then no sale will get you to try it again. To find out *why* a person makes a particular purchasing choice, you might examine the cost, ingredient list, or packaging of the two salad dressings.

Figure 1.1: Shopping sometimes involves a little scientific experimentation. You are interested in inventing a new type of salad that you can pack for lunch. You might buy a vegetable or salad dressing that you have not eaten before, to discover if you like it. If you like it, you will probably buy it again. That is a type of experiment.

There are many different areas of science, or *scientific disciplines*, but all scientific study involves:

- asking questions
- making observations
- relying on evidence to form conclusions

- being skeptical about ideas or results

Skepticism is an attitude of doubt about the truthfulness of claims that lack empirical evidence. **Scientific skepticism,** also referred to as skeptical inquiry, questions claims based on their scientific verifiability rather than accepting claims based on faith or anecdotes. Scientific skepticism uses critical thinking to analyze such claims and opposes claims which lack scientific evidence.

A Scientific View of the World

Science is based on the analysis of things that humans can observe either by themselves through their senses, or by using special equipment. Science therefore cannot explain anything about the natural world that is beyond what is observable by current means. The term *supernatural* refers to entities, events, or powers regarded as being beyond nature, in that such things cannot be explained by scientific means. They are not measurable or observable in the same way the natural world is, and so considered to be outside the realm of scientific examination.

When a natural occurrence which was once considered supernatural is understood in the terms of natural causes and consequences, it has a scientific explanation. For example, the flickering lights sometimes seen hovering over damp ground on still evenings or nights are commonly called *Will-o'-the-wisp.* This phenomena looks like a lamp or flame, and is sometimes said to move away if approached. A great deal of folklore surrounds the legend, such as the belief that the lights are lost souls or fairies attempting to lead travelers astray. However, science has offered several potential explanations for Will-o'-the-wisp from burning marsh gases to glowing fungi or animals that glow in a similar way to lightning bugs.

There is no fixed set of steps that scientists always follow and there is no single path that leads to scientific knowledge. There are, however, certain features of science that give it a very specific way of investigating something. You do not have to be a professional scientist to think like a scientist. Everyone, including you, can use certain features of scientific thinking to think critically about issues and situations in everyday life.

Science assumes that the universe is a vast single system in which the basic rules are the same, and thus nature, and what happens in nature, can be understood. Things that are learned from studying one part of the universe can be applied to other parts of the universe. For example, the same principles of motion and gravitation that explain the motion of falling objects on Earth also explain the orbit of the planets around the sun, and galaxies, as shown in **Figure** 1.2. As discussed below, as more and more information and knowledge is collected and understood, scientific ideas can change, still scientific knowledge usually stands the test of time. Science, however, cannot answer all questions.

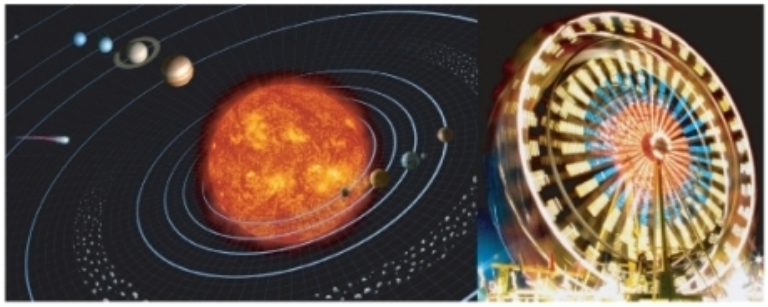

Figure 1.2: With some changes over the years, similar principles of motion have applied to different situations. The same scientific principles that help explain planetary orbits can be applied to the movement of a Ferris wheel.

Nature Can Be Understood

Science presumes that events in the universe happen in patterns that can be understood by careful study. Scientists believe that through the use of the mind, and with the help of instruments that extend the human senses, people can discover patterns in all of nature that can help us understand the world and the universe.

Scientific Ideas Can Change

Science is a process for developing knowledge. Change in knowledge about the natural world is expected because new observations may challenge the existing understanding of nature. No matter how well one theory explains a set of observations, it is possible that another theory may fit just as well or better, or may fit a still wider range of observations. In science, the testing and improving of theories goes on all the time. Scientists know that even if there is no way to gain complete knowledge about something, an increasingly accurate understanding of nature will develop over time.

The ability of scientists to make more accurate predictions about the natural world, from determining how a cancerous tumor develops a blood supply, to calculating the orbit of an asteroid, provides evidence that scientists are gaining an understanding of how the world works.

Scientific Knowledge Can Stand the Test of Time

Continuity and stability are as much characteristics of science as change is. Although scientists accept some uncertainty as part of nature, most scientific knowledge stands the test of time. A changing of ideas, rather than a complete rejection of the ideas, is the usual practice in science. Powerful ideas about nature tend to survive, grow more accurate and become

more widely accepted.

For example, in developing the theory of relativity, Albert Einstein did not throw out Issac Newton's laws of motion but rather, he showed them to be only a small part of the bigger, cosmic picture. That is, the Newtonian laws of motion have limited use within our more general concept of the universe. For example, the National Aeronautics and Space Administration (NASA) uses the Newtonian laws of motion to calculate the flight paths of satellites and space vehicles.

Science Cannot Offer Answers to All Questions

There are many things that cannot be examined in a scientific way. There are, for instance, beliefs that cannot be proved or disproved, such as the existence of supernatural powers, supernatural beings, or the meaning of life. In other cases, a scientific approach to a question and a scientific answer may be rejected by people who hold to certain beliefs.

Scientists do not have the means to settle moral questions surrounding good and evil, or love and hate, although they can sometimes contribute to the discussion of such issues by identifying the likely reasons for certain actions by humans and the possible consequences of these actions.

Scientific Methods

It can be difficult sometimes to define research methods in a way that will clearly distinguish science from non-science. However, there is a set of core principles that make up the "bones" of scientific research. These principles are widely accepted within the scientific community and in academia.

We learned earlier in this lesson that there is no fixed set of steps that scientists always follow during an investigation. Similarly, there is no single path that leads scientists to knowledge. There are, however, certain features of science that give it a very specific way of investigating things.

Scientific investigations examine, gain new knowledge, or build on previous knowledge about phenomena. A **phenomenon**, is any occurrence that is observable, such as the burning match shown in **Figure** 1.3. A phenomenon may be a feature of matter, energy, or time. For example, Isaac Newton made observations of the phenomenon of the moon's orbit. Galileo Galilei made observations of phenomena related to swinging pendulums. Although procedures vary from one field of scientific inquiry to another, certain features distinguish scientific inquiry from other types of knowledge. **Scientific methods** are based on gathering observable, empirical (produced by experiment or observation), and measurable evidence that is critically evaluated.

A **hypothesis** is a suggested explanation based on evidence that can be tested by observation

Figure 1.3: The combustion of this match is an observable event and therefore a phenomenon.

or experimentation. Experimenters may test and reject several hypotheses before solving a problem. A hypothesis must be testable; it gains credibility by being tested over and over again, and by surviving several attempts to prove it wrong.

Scientific Investigations

The scientific method is not a step by step, linear process. It is a way of learning about the world through the application of knowledge. Scientists must be able to have an idea of what the answer to an investigation is. Scientists will often make an observation and then form a hypothesis to explain why a phenomenon occurred. They use all of their knowledge and a bit of imagination in their journey of discovery.

Scientific investigations involve the collection of data through observation, the formation and testing of hypotheses by experimentation, and analysis of the results that involves reasoning.

Scientific investigations begin with observations that lead to questions. We will use an everyday example to show what makes up a scientific investigation. Imagine that you walk into a room, and the room is dark.

- You observe that the room appears dark, and you question why the room is dark.

- In an attempt to find explanations to this phenomenon, you develop several different *hypotheses*. One hypothesis might state that the room does not have a light source at all. Another hypothesis might be that the lights are turned off. Still, another might be that the light bulb has burnt out. Worse yet, you could be going blind.
- To discover the answer, you experiment. You feel your way around the room and find a light switch and turn it on. No light. You repeat the experiment, flicking the switch back and forth; still nothing.
- This means your first two hypotheses, that the room is dark because (1) it does not have a light source; and (2) the lights are off, have been rejected.
- You think of more experiments to test your hypotheses, such as switching on a flashlight to prove that you are not blind.
- In order to accept your last remaining hypothesis as the answer, you could predict that changing the light bulb will fix the problem. If your predictions about this hypothesis succeed (changing the light bulb fixes the problem), the original hypothesis is valid and is accepted.
- However, in some cases, your predictions will not succeed (changing the light bulb does not fix the problem), and you will have to start over again with a new hypothesis. Perhaps there is a short circuit somewhere in the house, or the power might be out.

The general process of a scientific investigation is summed up in **Figure** 1.4.

Table 1.1: **Common Terms Used in Scientific Investigations**

Term	Definition
Scientific Method	The process of scientific investigation.
Observation	The act of noting or detecting phenomenon by the senses. For example, taking measurements is a form of observation.
Hypotheses	A suggested explanation based on evidence that can be tested by observation or experimentation.
Scientific Reasoning	The process of looking for scientific reasons for observations.
Experiment	A test that is used to rule out a hypothesis or validate something already known.
Rejected Hypothesis	An explanation that is ruled out by experimentation.
Confirmed Hypothesis	An explanation that is **not** ruled out by repeated experimentation, and makes predictions that are shown to be true.
Inference	Developing new knowledge based upon old knowledge.

Table 1.1: (continued)

Term	Definition
Theory	A widely accepted hypothesis that stands the test of time. Theories are often tested, and usually not rejected.

Making Observations

Scientists first make observations that raise questions. An **observation** is the act of noting or detecting phenomenon through the senses. For example, noting that a room is dark is an observation made through sight.

Developing Hypotheses

In order to explain the observed phenomenon, scientists develop a number of possible explanations, or *hypotheses.* A hypothesis is a suggested explanation for a phenomenon or a suggested explanation for a relationship between many phenomena. Hypotheses are always based on evidence that can be tested by observation or experimentation. Scientific investigations are required to test hypotheses. Scientists mostly base hypotheses on prior observations or on extensions of existing scientific explanations.

A hypothesis is not really an educated guess. To define a hypothesis as "an educated guess" is like calling a tricycle a "vehicle with three." The definition leaves out the concept's most important and characteristic feature: the purpose of hypotheses. People generate hypotheses as early attempts to explain patterns observed in nature or to predict the outcomes of experiments. For example, in science, one could correctly call the following statement a hypothesis: identical twins can have different personalities because the environment influences personality.

Evaluating Hypotheses

Scientific methods require hypotheses that are falsifiable, that is, they must be framed in a way that allows other scientists to prove them false. Proving a hypothesis to be false is usually done by observation. However, confirming or failing to falsify a hypothesis does not necessarily mean the hypothesis is true.

For example, a person comes to a new country and observes only white sheep. This person might form the hypothesis: "All sheep in this country are white." This statement can be called a hypothesis, because it is falsifiable - it can be tested and proved wrong; anyone could falsify the hypothesis by observing a single black sheep, shown in **Figure** 1.5. If the

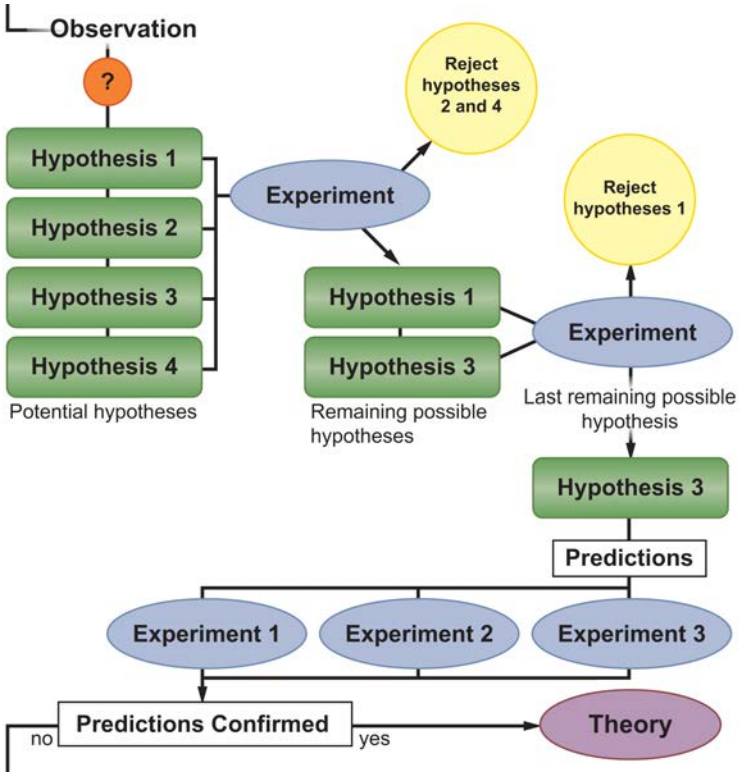

Figure 1.4: The general process of scientific investigations. A diagram that illustrates how scientific investigation moves from observation of phenomenon to a theory. The progress is not as straightforward as it looks in this diagram. Many times, every hypothesis is falsified which means the investigator will have to start over again.

experimental uncertainties remain small (could the person reliably distinguish the observed black sheep from a goat or a small horse), and if the experimenter has correctly interpreted the hypothesis, finding a black sheep falsifies the "only white sheep" hypothesis. However, you cannot call a failure to find non-white sheep as proof that no non-white sheep exist.

Figure 1.5: The statement "there are only white sheep in this country" is a scientific hypothesis because it is open to being falsified. However, a failure to see a black sheep will not necessarily falsify the hypothesis.

Scientific Reasoning

Any useful hypothesis will allow predictions based on reasoning. Reasoning can be broken down into two categories: **deduction** and **induction**. Most reasoning in science is done through induction.

Deductive Reasoning (Deduction)

Deduction involves determining a single fact from a general statement; it is only as accurate as the statement.

For example, if the teacher said she checks homework every Monday, she will check homework next Monday.

Deductions are intended to have reasoning that is valid. The reasoning in this argument is valid, because there is no way in which the reasons 1 and 2, could be true and the conclusion, 3, be false:

- Reason 1: All humans are mortal.
- Reason 2: Albert Einstein is a human.
- Conclusion: Albert Einstein is mortal (**Figure** 1.6).

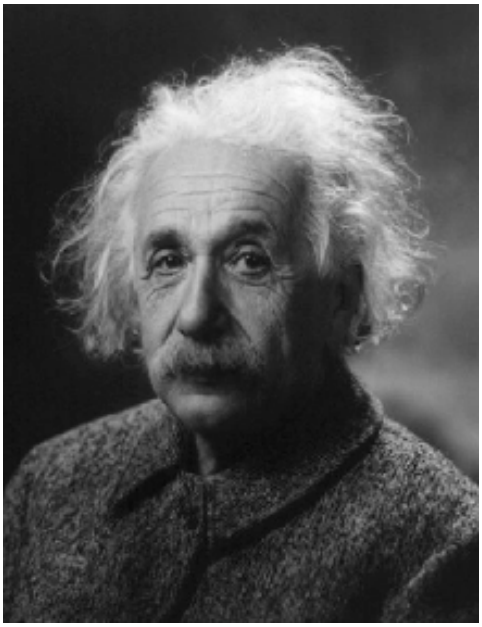

Figure 1.6: Albert Einstein (1879–1955) Deductive reasoning has helped us determine that Albert Einstein is a mortal being.

Inductive Reasoning (Induction)

Induction involves determining a general statement that is very likely to be true, from several facts.

For example, if we have had a test every Tuesday for the past three months, we will have a test next Tuesday (and every Tuesday after that).

Induction contrasts strongly with deduction. Even in the best, or strongest, cases of induction, the truth of the reason does not guarantee the truth of the conclusion. Instead, the conclusion of an inductive argument is very likely to be true; you cannot be fully sure it is true because you are making a prediction that has yet to happen.

A classic example of inductive reasoning comes from the philosopher David Hume:

- Reason: The sun has risen in the east every morning up until now.
- Conclusion: The sun will also rise in the east tomorrow.

Inductive reasoning involves reaching conclusions about unobserved things on the basis of what has been observed already. Inferences about the past from present evidence, such as in archaeology, are induction. Induction could also be across outer space, as in astronomy, where conclusions about the whole universe are drawn from the limited number of things we are able to observe.

Experiments

A scientific experiment must have the following features:

- a control, so variables that could affect the outcome are reduced
- the variable being tested reflects the phenomenon being studied
- the variable can be measured accurately, to avoid experimental error
- the experiment must be reproducible.

An **experiment** is a test that is used to eliminate one or more of the possible hypotheses until one hypothesis remains. The experiment is a cornerstone in the scientific approach to gaining deeper knowledge about the physical world. Scientists use the principles of their hypothesis to make predictions, and then test them to see if their predictions are confirmed or rejected.

Scientific experiments involve **controls**, or subjects that are not tested during the investigation. In this way, a scientist limits the factors, or *variables* that can cause the results of an investigation to differ. A **variable** is a factor that can change over the course of an experiment. **Independent variables** are factors whose values are controlled by the experimenter to determine its relationship to an observed phenomenon (the dependent variable). **Dependent variables** change in response to the independent variable. **Controlled variables** are also important to identify in experiments. They are the variables that are kept constant to prevent them from influencing the effect of the independent variable on the dependent variable.

For example, if you were to measure the effect that different amounts of fertilizer have on plant growth, the independent variable would be the amount of fertilizer used (the changing factor of the experiment). The dependent variables would be the growth in height and/or mass of the plant (the factors that are influenced in the experiment). The controlled variables include the type of plant, the type of fertilizer, the amount of sunlight the plant gets, the size of the pots you use. The controlled variables are controlled by you, otherwise they would influence the dependent variable.

In summary:

- The independent variable answers the question "What do I change?"
- The dependent variables answer the question "What do I observe?"
- The controlled variables answer the question "What do I keep the same?"

Experimental Design

Controlled Experiments

In an old joke, a person claims that they are snapping their fingers "to keep tigers away," and justifies their behavior by saying, "See, it works!" While this experiment does not falsify the hypothesis "snapping your fingers keeps tigers away," it does not support the hypothesis either, because not snapping your fingers will also keep tigers away. It also follows that not snapping your fingers will not cause tigers to suddenly appear (**Figure** 1.7).

Figure 1.7: Are tigers really scared of snapping fingers, or is it more likely they are just not found in your neighborhood? Considering which of the hypotheses is more likely to be true can help you arrive at a valid answer. This principle, called states that the explanation for a phenomenon should make as few assumptions as possible. In this case, the hypothesis "there are no tigers in my neighborhood to begin with" is more likely, because it makes the least number of assumptions about the situation.

To demonstrate a cause and effect hypothesis, an experiment must often show that, for example, a phenomenon occurs after a certain treatment is given to a subject, and that the phenomenon does not occur in the absence of the treatment.

One way of finding this out is to perform a controlled experiment. In a **controlled experiment,** two identical experiments are carried out side-by-side. In one of the experiments

the independent variable being tested is used, in the other experiment, the control, or the independent variable is not used.

A controlled experiment generally compares the results obtained from an experimental sample against a control sample. The control sample is almost identical to the experimental sample except for the one variable whose effect is being tested. A good example would be a drug trial. The sample or group receiving the drug would be the experimental group, and the group receiving the placebo would be the control. A **placebo** is a form of medicine that does not contain the drug that is being tested.

Controlled experiments can be conducted when it is difficult to exactly control all the conditions in an experiment. In this case, the experiment begins by creating two or more sample groups that are similar in as many ways as possible, which means that both groups should respond in the same way if given the same treatment.

Once the groups have been formed, the experimenter tries to treat them identically except for the one variable that he or she wants to study (the independent variable). Usually neither the patients nor the doctor know which group receives the real drug, which serves to isolate the effects of the drug and allow the researchers to be sure the drug does work, and that the effects seen in the patients are not due to the patients believing they are getting better. This type of experiment is called a **double blind** experiment.

Controlled experiments can be carried out on many things other than people; some are even carried out in space! The wheat plants in **Figure** 1.8 are being grown in the International Space Station to study the effects of microgravity on plant growth. Researchers hope that one day enough plants could be grown during spaceflight to feed hungry astronauts and cosmonauts. The investigation also measured the amount of oxygen the plants can produce in the hope that plants could become a cheap and effective way to provide oxygen during space travel.

Experiments Without Controls

The term **experiment** usually means a controlled experiment, but sometimes controlled experiments are difficult or impossible to do. In this case researchers carry out **natural experiments**. When scientists conduct a study in nature instead of the more controlled environment of a lab setting, they cannot control variables such as sunlight, temperature, or moisture. Natural experiments therefore depend on the scientist's observations of the system under study rather than controlling just one or a few variables as happens in controlled experiments.

For a natural experiment, researchers attempt to collect data in such a way that the effects of all the variables can be determined, and where the effects of the variation remains fairly constant so that the effects of other factors can be determined. Natural experiments are a common research tool in areas of study where controlled experiments are difficult to carry out.

Figure 1.8: Spaceflight participant Anousheh Ansari holds a miniature wheat plant grown in the Zvezda Service Module of the International Space Station.

Examples include: **astronomy** -the study of stars, planets, comets, galaxies and phenomena that originate outside Earth's atmosphere, **paleontology** - the study of prehistoric life forms through the examination of fossils, and **meteorology** - the study of Earth's atmosphere.

In astronomy it is impossible, when testing the hypothesis "suns are collapsed clouds of hydrogen", to start out with a giant cloud of hydrogen, and then carry out the experiment of waiting a few billion years for it to form a sun. However, by observing various clouds of hydrogen in various states of collapse, and other phenomena related to the hypothesis, such as the nebula shown in **Figure** 1.9, researchers can collect data they need to support (or maybe falsify) the hypothesis.

An early example of this type of experiment was the first verification in the 1600s that light does not travel from place to place instantaneously, but instead has a speed that can be measured. Observation of the appearance of the moons of Jupiter were slightly delayed when Jupiter was farther from Earth, as opposed to when Jupiter was closer to Earth. This phenomenon was used to demonstrate that the difference in the time of appearance of the moons was consistent with a measurable speed of light.

Natural Experiments

There are situations where it would be wrong or harmful to carry out an experiment. In these cases, scientists carry out a natural experiment, or an investigation without an experiment. For example, alcohol can cause developmental defects in fetuses, leading to mental and physical problems, through a condition called fetal alcohol syndrome.

Certain researchers want to study the effects of alcohol on fetal development, but it would

Figure 1.9: The Helix nebula, located about 700 light-years away in the constellation Aquarius, belongs to a class of objects called . Planetary nebulae are the remains of stars that once looked a lot like our sun. When sun-like stars die, they puff out their outer gaseous layers. These layers are heated by the hot core of the dead star, called a white dwarf, and shine with infrared and visible colors. Scientists can study the birth and death of stars by analyzing the types of light that are emitted from nebulae.

be considered wrong or *unethical* to ask a group of pregnant women to drink alcohol to study its effects on their children. Instead, researchers carry out a natural experiment in which they study data that is gathered from mothers of children with fetal alcohol syndrome, or pregnant women who continue to drink alcohol during pregnancy. The researchers will try to reduce the number of variables in the study (such as the amount or type of alcohol consumed), which might affect their data. It is important to note that the researchers do not influence or encourage the consumption of alcohol; they collect this information from volunteers.

Field Experiments

Field experiments are so named to distinguish them from lab experiments. Field experiments have the advantage that observations are made in a natural setting rather than in a human-made laboratory environment. However, like natural experiments, field experiments can get contaminated, and conditions like the weather are not easy to control. Experimental conditions can be controlled with more precision and certainty in the lab.

Predictions

A **prediction** is a statement that tells what will happen under specific conditions. It can be expressed in the form: *If A is true, then B will also be true.* Predictions are based on confirmed hypotheses shown to be true or not proved to be false.

For researchers to be confident that their predictions will be useful and descriptive, their data must have as few errors as possible. **Accuracy** is the measure of how close a calculated or measured quantity is to its actual value. Accuracy is closely related to **precision**, also called reproducibility or repeatability. Reproducibility and repeatability of experiments are cornerstones of scientific methods. If no other researcher can reproduce or repeat the results of a certain study, then the results of the study will not be accepted as valid. Results are called valid only if they are both accurate and precise.

A useful tool to help explain the difference between accuracy and precision is a target, shown in **Figure** 1.10. In this analogy, repeated measurements are the arrows that are fired at a target. Accuracy describes the closeness of arrows to the bulls eye at the center. Arrows that hit closer to the bulls eye are more accurate. Arrows that are grouped together more tightly are more precise.

Experimental Error

An **error** is a boundary on the precision and accuracy of the result of a measurement. Some errors are caused by unpredictable changes in the measuring devices (such as balances, rulers, or calipers), but other errors can be caused by reading a measuring device incorrectly or by

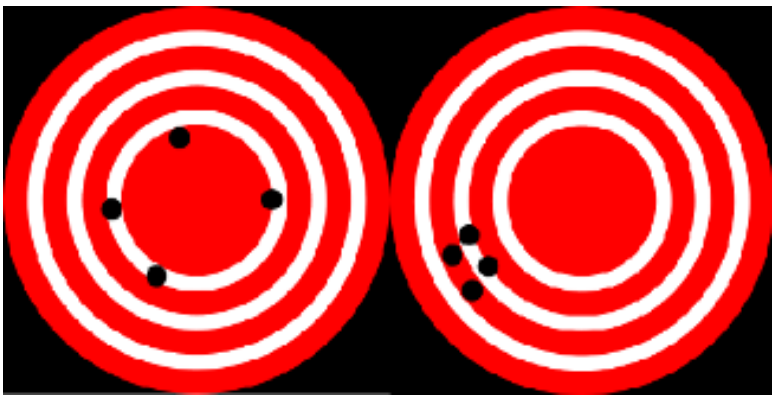

Figure 1.10: A visual analogy of accuracy and precision. Left target: High accuracy but low precision; Right target: low accuracy but high precision. The results of calculations or a measurement can be accurate but not precise; precise but not accurate; neither accurate nor precise; or accurate and precise. A collection of bulls eyes right around the center of the target would be both accurate and precise.

using broken or malfunctioning equipment. Such errors can have an impact on the reliability of the experiment's results; they affect the accuracy of measurements. For example, you use a balance to obtain the mass of a 100 gram block. Three measurements that you get are: 93.1 g, 92.0 g, and 91.8 g. The measurements are precise, as they are close together, but they are not accurate.

If the cause of the error can be identified, then it can usually be eliminated or minimized. Reducing the number of possible errors by careful measurement and using a large enough sample size to reduce the effect of errors will improve the reliability of your results.

Scientific Theories

Scientific theories are hypotheses which have stood up to repeated attempts at falsification and are thus supported by a great deal of data and evidence. Some well known biological theories include the theory of evolution by natural selection, the cell theory (the idea that all organisms are made of cells), and the germ theory of disease (the idea that certain microbes cause certain diseases). The scientific community holds that a greater amount of evidence supports these ideas than contradicts them, and so they are referred to as theories.

In every day use, people often use the word **theory** to describe a guess or an opinion. For example, "I have a theory as to why the light bulb is not working." When used in this common way, "theory" does not have to be based on facts, it does not have to be based on a true description of reality. This usage of the word theory often leads to a misconception that can be best summed up by the phrase "It's not a fact, it's only a theory." In such everyday usage, the word is most similar to the term hypothesis.

Scientific theories are the equivalent of what in everyday speech we would refer to as *facts*. In principle, scientific theories are always subject to corrections or inclusion in another, wider theory. As a general rule for use of the term, theories tend to deal with broader sets of phenomena than do hypotheses, which usually deal with much more specific sets of phenomena or specific applications of a theory.

Constructing Theories

In time, a confirmed hypothesis may become part of a theory or may grow to become a theory itself. Scientific hypotheses may be mathematical models. Sometimes they can be statements, stating that some particular instance of the phenomenon under examination has some characteristic and causal explanations. These theories have the general form of universal statements, stating that every instance of the phenomenon has a particular characteristic.

A hypothesis may predict the outcome of an experiment in a laboratory or the observation of a natural phenomenon. A hypothesis should also be falsifiable, and one cannot regard a hypothesis or a theory as scientific if it does not lend itself to being falsified, even in the future. To meet the "falsifiable" requirement, it must at least in principle be possible to make an observation that would disprove the hypothesis. A falsifiable hypothesis can greatly simplify the process of testing to determine whether the hypothesis can be proven to be false. Scientific methods rely heavily on the falsifiability of hypotheses by experimentation and observation in order to answer questions. Philosopher Karl Popper suggested that all scientific theories should be falsifiable; otherwise they could not be tested by experiment.

A **scientific theory** must meet the following requirements:

- it must be consistent with pre-existing theory in that the pre-existing theory has been experimentally verified, though it may often show a pre-existing theory to be wrong in an exact sense
- it must be supported by many strands of evidence rather than a single foundation, ensuring that it is probably a good approximation, if not totally correct.

Also, a theory is generally only taken seriously if it:

- allows for changes to be made as new data are discovered, rather than claiming absolute certainty.
- is the most straight forward explanation, and makes the fewest assumptions about a phenomenon (commonly called "passing the Occam's razor test").

This is true of such established theories as special relativity, general relativity, quantum mechanics, plate tectonics, and evolution. Theories considered scientific meet at least most, but ideally all, of these extra criteria.

In summary, to meet the status of a scientific theory, the theory must be falsifiable or testable. Examples of scientific theories in different areas of science include:

- **Astronomy**: Big Bang Theory
- **Biology**: Cell Theory; Theory of Evolution; Germ Theory of Disease
- **Chemistry**: Atomic Theory; Kinetic Theory of Gases
- **Physics**: General Relativity; Special Relativity; Theory of Relativity; Quantum Field Theory
- **Earth Science**: Giant Impact Theory; Plate Tectonics

Currently Unverifiable Theories

The term theory is sometimes stretched to refer to theoretical speculation which is currently unverifiable. Examples are string theory and various theories of everything. **String theory** is a model of physics, which predicts the existence of many more dimensions in the universe than the four dimensions that current science understands (length, width, height, and space-time). **A theory of everything** is a hypothetical theory in physics that fully explains and links together all known physical phenomena.

For a scientific theory to be valid it must be verified experimentally. Many parts of the string theory are currently untestable due to the large amount of energy that would be needed to carry out the necessary experiments as well as the high cost of conducting them. Therefore string theory may not be tested in the foreseeable future. Some scientists have asked if it even deserves to be called a scientific theory because it is not falsifiable.

Superseded Theories

A **superseded,** or obsolete, scientific theory is a theory that was once commonly accepted, but for whatever reason is no longer considered the most complete description of reality by mainstream science. It can also mean a falsifiable theory which has been shown to be false. Giraffes, shown in **Figure** 1.11, are often used in the explanation of Lamarck's superseded theory of evolution. In Lamarckism, a giraffe is able to lengthen its neck over its life time, for example by stretching to reach higher leaves. That giraffe will then have offspring with longer necks. The theory has been superseded by the understanding of natural selection on populations of organisms as the main means of evolution, not physical changes to a single organism over its lifetime.

Scientific Laws

Scientific laws are similar to scientific theories in that they are principles which can be used to predict the behavior of the natural world. Both scientific laws and scientific the-

Figure 1.11: Superseded theories like Lamarck's theory of evolution are theories that are now considered obsolete and have been replaced by newer theories that have more evidence to support them; in Lamarck's case, his theory was replaced by Darwin's theory of evolution and natural selection, which will be discussed in the chapter on .

ories are typically well-supported by observations and/or experimental evidence. Usually scientific laws refer to rules for how nature will behave under certain conditions. Scientific theories are more overarching explanations of how nature works and why it exhibits certain characteristics.

A **physical law** or law of nature is a scientific generalization based on a sufficiently large number of empirical observations that it is taken as fully verified.

Isaac Newton's law of gravitation is a famous example of an established law that was later found not to be universal—it does not hold in experiments involving motion at speeds close to the speed of light or in close proximity of strong gravitational fields. Outside these conditions, Newton's laws remain an excellent model of motion and gravity.

Scientists never claim absolute knowledge of nature or the behavior of the subject of the field of study. A scientific theory is always open to falsification, if new evidence is presented. Even the most basic and fundamental theories may turn out to be imperfect if new observations are inconsistent with them. Critical to this process is making every relevant part of research publicly available. This allows peer review of published results, and it also allows ongoing reviews, repetition of experiments and observations by many different researchers. Only by meeting these expectations can it be determined how reliable the experimental results are for possible use by others.

Lesson Summary

- Scientific skepticism questions claims based on their scientific verifiability rather than accepting claims based on faith or anecdotes. Scientific skepticism uses critical thinking to analyze such claims and opposes claims which lack scientific evidence.
- Science is based on the analysis of things that humans can observe either by themselves through their senses, or by using special equipment. Science therefore cannot explain anything about the natural world that is beyond what is observable by current means. Supernatural things cannot be explained by scientific means.
- Scientific investigations involve the collection of data through observation, the formation and testing of hypotheses by experimentation, and analysis of the results that involves reasoning.
- In a controlled experiment, two identical experiments are carried out side-by-side. In one of the experiments the independent variable being tested is used, in the other, the control, or the independent variable is not used.
- Any useful hypothesis will allow predictions based on reasoning. Reasoning can be broken down into two categories: deduction and induction. Most reasoning in science is formed through induction.
- A variable is a factor that can change over the course of an experiment. Independent variables are factors whose values are controlled by the experimenter to determine its relationship to an observed phenomenon (the dependent variable). Dependent variables change in response to the independent variable.
- Scientific theories are hypotheses which have stood up to repeated attempts at falsification and are thus supported by much data and evidence.

Review Questions

1. What is the goal of science?
2. Distinguish between a hypothesis and a theory.
3. The makers of two types of plant fertilizers claim that their product grows plants the fastest and largest. Design an experiment that you could carry out to investigate the claims.
4. Identify how hypotheses and predictions are related.
5. What is the difference between the everyday term "theory" and the term "scientific theory?"
6. Identify two ways that scientists can test hypotheses.
7. Outline the difference between inductive and deductive reasoning.
8. What is the range of processes that scientists use to carry out a scientific investigation called?
9. To ensure that their results are not due to chance, scientists will usually carry out an experiment a number of times, a process called replication. A scientist has two types of plants and she wants to test which plant produces the most oxygen under

sunny conditions outdoors. Devise a practical experimental approach, incorporating replication of the experiment.

10. In taking measurements, what is the difference between accuracy and precision?
11. Name two features that a hypothesis must have, to be called a scientific hypothesis.
12. Identify two features that a theory must have, to qualify as a scientific theory.
13. Give an example of a superseded theory.
14. Can a hypothesis take the form of a question? Explain your answer.
15. Why is it a good idea to try to reduce the chances of errors happening in an experiment?

Further Reading / Supplemental Links

- http://www.nap.edu/readingroom/books/obas/
- http://www.project2061.org/publications/sfaa/online/chap1.htm#inquiry
- http://www.nasa.gov/mission_pages/station/science/experiments/PESTO.html#applications
- http://biology.plosjournals.org/perlserv/?request=index-html&issn=1545-7885&ct=1
- http://biology.clc.uc.edu/courses/bio114/spontgen.htm
- http://www.estrellamountain.edu/faculty/farabee/biobk/diversity.htm
- http://www.nasa.gov/mission_pages/station/main/index.html
- http://books.nap.edu/html/climatechange/summary.html
- http://www.cisci.net/about.php?lang=1
- http://www.aaas.org/news/releases/2006/pdf/0219boardstatement.pdf

Vocabulary

control Something that is not tested during the investigation.

controlled experiment Two identical experiments are carried out side-by-side; in one of the experiments the independent variable being tested is used, in the other experiment, the control, or the independent variable is not used.

controlled variables Variables that are kept constant to prevent influencing the effect of the independent variable on the dependent variable.

deduction Involves determining a single fact from a general statement.

dependent variable Changes in response to the independent variable.

experiment A test that is used to eliminate one or more of the possible hypotheses until one hypothesis remains.

hypothesis A suggested explanation based on evidence that can be tested by observation or experimentation.

independent variable Factor(s) whose values are controlled by the experimenter to determine its relationship to an observed phenomenon (the dependent variable).

induction Involves determining a general statement that is very likely to be true, from several facts.

observation The act of noting or detecting phenomenon through the senses. For example, noting that a room is dark is an observation made through sight.

Occam's razor States that the explanation for a phenomenon should make as few assumptions as possible.

phenomenon Is any occurrence that is observable.

scientific methods Based on gathering observable, empirical (produced by experiment or observation) and measurable evidence that is critically evaluated.

scientific skepticism Questions claims based on their scientific verifiability rather than accepting claims based on faith or anecdotes.

variable A factor that can change over the course of an experiment.

Points to Consider

The Points to Consider section throughout this book is intended to have students think about material not yet presented. These points are intended to lead students into the next lesson or chapter.

- Science is a particular way in which people examine and ask questions about the world. Can you think of other ways in which people examine and ask questions about the world?
- Consider the importance of replication in an experiment and how replication of an experiment can affect results.
- Scientists often disagree among themselves about scientific findings, and communicate such disagreement at science conferences, through science articles in magazines, or science papers and in scientific journals. Can you think of other ways in which scientists could communicate so that the public can get a better idea of what the "hot topics" in science are?

1.2 Lesson 1.2: Communicating Ideas

Lesson Objectives

- Outline the need for scientists to be able to share their ideas and findings with each other.
- Identify the role of graphics in presenting results of an investigation.
- Identify the role of peer review in the communication of ideas.
- Examine how ethics are applied to communicating ideas and research.
- Compare scientist to scientist communication to scientist to public communication.
- Identify the benefits of studying science, even if you do not intend on becoming a scientist.
- List three things that can influence scientific research.
- Identify two ways that biotechnology has affected our lives.

Introduction

The reliability of scientific knowledge comes partly from the objectivity of scientific methods, and also from scientists discussing ideas with each other. In talking with each other, researchers must use more than just their scientific understanding of the world. They must also be able to convince a community of their peers of the correctness of their concepts and ideas.

Scientist to Scientist Communication

A wide range of scientific literature is published and it is a format where scientific debates are properly carried out and reviewed. This includes scientific publications that report original research within a scientific field and can comprise of the following:

- scientific articles published in scientific journals
- books written by one or a small number of co-authors who are researchers
- presentations at academic conferences, especially those organized by societies (for example, the American Association for the Advancement of Science)
- government reports
- scientific publications on the internet
- books, technical reports, pamphlets, and working papers issued by individual researchers or research organizations

Scientific journals communicate and document the results of research carried out in universities and various other research institutions. They are like a type of magazine that contains many articles which are written by different researchers about their ideas and discoveries.

Most scientific journals cover a single scientific field and publish the research within that field; the research is normally expressed in the form of a scientific paper.

An **academic conference** is a conference for researchers (not always academics) to present and discuss their work. Together with scientific journals, conferences are an important channel for exchange of ideas between researchers. Generally, work is shared in the form of visual posters or short presentations lasting about 10 to 30 minutes. These are usually followed by discussion. A researcher is presenting his work to his peers in **Figure** 1.12.

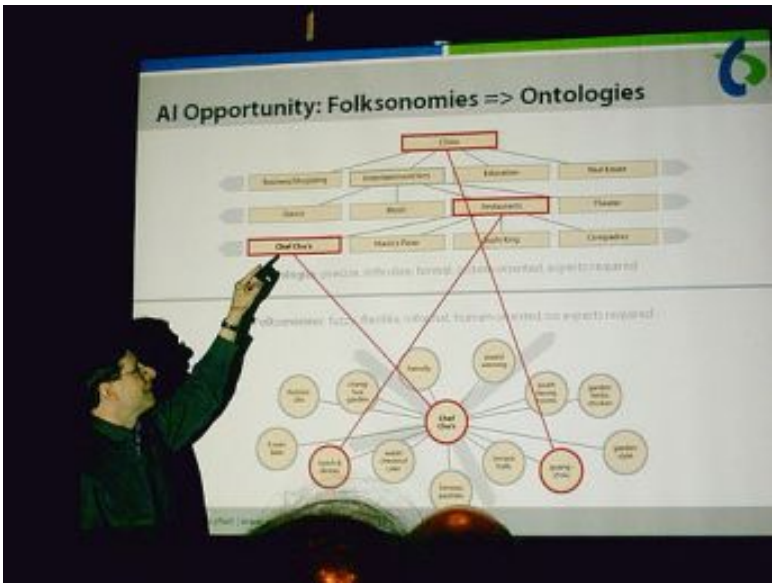

Figure 1.12: A presentation at an academic conference. At conferences, scientists are able to share ideas and their research results with many people at one time, and can talk directly to other researchers and answer their questions.

Types of Scientific Publications: Scientific Journals

A scientific journal is a publication that reports new research, and sometimes contains general science news articles. Most journals are highly specialized for a particular field of research such as biochemistry, microbiology, or botany. However, some of the oldest journals such as *Nature* publish articles and scientific papers across a wide range of scientific fields. The journals shown in **Figure** 1.13 have a similar look and layout to science journals.

Scientific journals contain articles that have been peer reviewed in an attempt to ensure that articles meet the journal's standards of quality, and scientific validity. A scientific journal is not usually read casually as you would read a magazine. Some of the content can be very dense and detailed.

The publication of the results of research is an essential part of the scientific process. The

researcher who has written the paper must give enough details about their experiments so that an independent researcher could repeat the experiment to verify the results.

The significance of these different parts of scientific literature differs between science disciplines and has changed over time. Peer-reviewed journal articles remain the most common publication type and have the highest level of trust. However, journals vary enormously in their prestige and importance, and the value of a published article depends on the journal, review process and the degree that it is referenced by other scientists.

Some well known and well respected science and medical journals include:

- Science
- Nature
- Proceedings of the National Academy of Sciences of the United States of America (PNAS)
- Public Library of Science (PLoS)
- Cell
- Journal of the American Medical Association (JAMA)
- The Lancet
- Journal of Theoretical Biology

Figure 1.13: These research journals publish research papers written by economists, people who study the economy, and related issues. However, the layout of research journals is very similar.

Science Articles

New research is usually written up in the form of a **scientific article**, which often appear in journals. A scientific article has a standardized structure, which varies only slightly between the different sciences. This format can also be used for your lab reports as part of this class.

It is not really the format of the article that is important, but what lies behind it or the content. However, several key format requirements need to be met by every science article:

1. The title should be short and indicate the contents of the article.

2. The names of all authors that were involved in the research should be given. Where the authors work or study should also be listed.

3. The first section is normally an **abstract**: a one-paragraph summary of the work. The abstract is intended to serve as a quick guide for the reader as to the content of the article.

4. The format should be able to be stored in a library so that scientists years later will be able to recover any document in order to study and assess it

5. The content of the study should be presented in the context of previous scientific investigations, by citing related documents in the existing literature. This is usually in a section called an **introduction**.

6. Observations that were made, and measurements that were taken are described in a section usually called **Materials and Methods**. The experiments should be described in such a way that other scientists in the same or related fields can repeat the experiments and observations and know whether he or she gets the same results. This is called **reproducibility**.

7. Similarly, the results of the investigation are given in a section called, **results**. Data should be presented in tabular or graphic form (images, charts, graphs, photos, or diagrams, shown in **Figure** 1.14. Graphics should have a caption to explain what they are showing.

8. Interpretation of the meaning of the results is usually addressed in a **discussion** and/or **conclusion** section. The conclusions drawn should be based on previous studies and/or new scientific results. They should also be written in a way such that any reader with knowledge of the field can follow the argument and confirm that the conclusions are sound.

9. Finally, a **references** or **literature cited** section lists the sources cited by the authors in the format required by the journal.

Sources of Information

The reliability of information is dependent on whether the information appears in a primary source, secondary source, or a tertiary source.

Most research studies are first published in a scientific journal, which are referred to as **primary sources**. Technical reports, for minor research results are also primary sources.

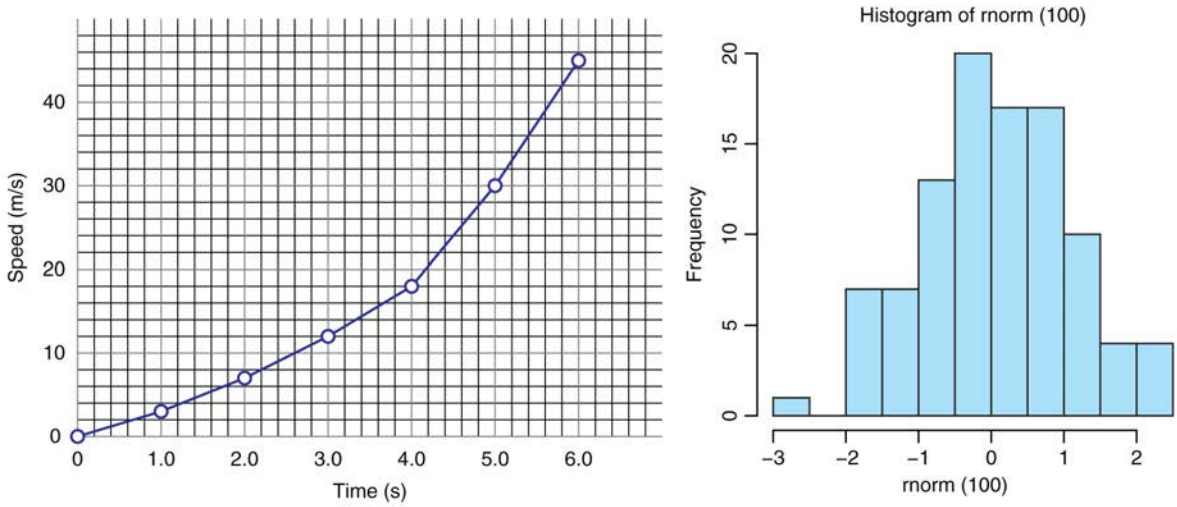

Figure 1.14: Examples of a graph and a chart that can be used to communicate data in scientific papers. (l-r) Graph showing how speed increases over time, Histogram which illustrates the frequency a particular trait appears in a population. Graphics help to illustrate ideas that would otherwise be too confusing to describe in words only.

Secondary sources include articles in review journals (collections of recent research articles on a topic). Review journals are usually published to highlight advances and new lines of research in specific areas, such as human genetics, specific medical disorders (such as heart disease), neurology (the study of the nervous system) or malacology, (the study of snails and other mollusks). Large projects, broad arguments, or a mix of different types of articles may appear in a book. Review journals and books are referred to as secondary sources. Tertiary sources might include encyclopedias and news articles which are generally written for the public to read.

Peer Review

Scientists are expected to report their work truthfully and honestly. They are also expected to have their work reviewed by fellow scientists. This process is called peer review.

Peer review is a process of opening a scientist's research or ideas (in the form of a scientific paper) to examination by other scientists who are experts in the same field. The peer review process aims to make authors meet the standards of their area of study, and to meet the expected standards of science in general. Publications that have not undergone peer review are likely to be regarded with suspicion by scholars and professionals in many fields. However, even peer reviewed journals can contain errors.

A reason for the need for peer review is that it is rare for an individual author or research team to spot every mistake or flaw in a complicated piece of work. The review process provides an opportunity for improvement because a person with special expertise or experience reads the research paper before it is published. Typically, for publication in a science journal, it is also a requirement that the research is new and useful. Since reviewers are normally selected from experts in the areas of science covered by the article, the process of peer review is considered vital to establishing a reliable body of research and knowledge. Therefore, showing work to other scientists increases the likelihood that weaknesses will be found and corrected.

The process of peer review is not designed to detect fraud. As a result, there is usually a large scandal when a researcher and author of a science paper is found to have falsified the research in an article, as many other researchers may have relied upon their original research for their own work or the researcher could have received grant money based on falsified research. Peer review of scientific work assumes that the article reviewed has been honestly written. Usually reviewers do not have full access to the data from which the paper has been written, so they trust that the author is being truthful and honest.

Research Bias

It is important for the researcher to remain neutral or objective when conducting scientific research. A **bias** is a position for favoring one particular point of view over another, and it is usually based on preconceived ideas about a situation. The inability of a human being to remain completely objective is the source of such bias in research. Nevertheless, a researcher or their study is generally said to be *biased* only if the researcher's judgment is influenced by the biases they hold, which could influence their research results.

For example, you want to test whether your dog, Frankie, prefers his regular food or the super expensive brand dog food that you have just bought on sale. You would put each food in a bowl and offer both foods to Frankie at his meal time. However, you secretly hope he prefers his regular food because it is half the price of the more expensive food and you can buy it in the store down the road. Frankie takes a couple of mouthfuls of his regular food, but gobbles up all of the expensive food. You may think, "Well, he did eat some of regular food, so he still likes it," when in fact Frankie clearly preferred the expensive brand. You buy the regular food anyhow. Whether you like it or not, you are biased toward the regular dog food.

This example above is greatly simplified, but, illustrates how personal opinions may influence an investigation.

Another type of bias, called a *systematic bias* is introduced from a flaw in measurements. For example, an incorrectly calibrated thermostat may consistently read several degrees hotter or colder than actual temperature. As a consequence, systematic bias commonly leads to systematic errors in the results of an investigation. Peer review can usually detect systematic biases in a research study.

Conflict of Interest

A **conflict of interest** is a situation in which a researcher has professional or personal interests that are at odds with each other. For example, a researcher is about to investigate a new headache medicine from a drug company called Tinneas. The researcher carries out experiments and finds that the medicine works very well. End of story, right? Not exactly.

Later it is discovered that the researcher owns Tinneas stock. This means he owns part of the company. Even if everything was done correctly during the experiment, and the drug really does work, this researcher has a conflict of interest. As an owner of the company, he will earn money if the drug works, but will lose money if the drug does not work. Therefore, any scientist that may have a reason to favor one particular result from an investigation should not be involved in that investigation.

Competing interests can make it difficult for a person to carry out his or her duties without bias. A conflict of interest exists even if no wrong has been done, or nothing results from it. A conflict of interest can affect the public confidence in the person, a profession, or company.

Scientific Misconduct

When presenting their research to others, an ethical scientist would not falsify results, lie about their results, or plagiarize (steal other peoples ideas or work).

Scientific misconduct is the violation of these standard codes of scholarly conduct and ethical behavior in professional scientific research. Scientific misconduct may take place simply out of reputation. For example, academic scientists are often under enormous pressure to produce publications in peer reviewed journals. Alternatively, there may be commercial or political motivations where the financial or political success of a project depends on publishing evidence of a procedure working or not working. The consequences of scientific misconduct can be severe at a personal and professional level for the people involved. In addition, there are public health concerns attached to the promotion of medical or other procedures that are founded on doubtful research results.

Truth and Honesty in Research and Communication

Some instances of scientific fraud and scientific misconduct have gone through review and were detected only after other groups tried and failed to replicate the published results. An example is the case of physicist Jan Hendrik Schön, in which a total of fifteen papers on microelectronics and nanotechnology were accepted for publication in the top ranked journals, *Nature* and *Science*, following the usual peer review process. All fifteen were found to be fraudulent and were then withdrawn. The fraud was found, not by the peer review process, but by other research groups who tried and failed to reproduce the results of the paper.

Likewise, biomedical scientist Hwang Woo-Suk, rose to fame after claiming a series of breakthroughs in the field of stem cell research. He was once considered one of the pioneering experts in the field of stem cell research, because of his success in creating cloned human embryonic stem cells. However, his two most famous research articles on the cloning experiments were found to contain large amounts of fabricated data. Hwang's papers were retracted (withdrawn from publication), he lost his job at the university where he worked, and also lost his research funding.

Scientist to Public Communication

Science has become such a part of modern life that it is necessary to communicate the achievements, news, and ambitions of scientists to a wider audience. Scientists need to be able to tell each other and the public about their research and the results of their research. These two groups make up two very different audiences for scientists, however. The first audience is made up of their peers-fellow scientists who have an advanced understand of the technical language and procedures that are involved in scientific investigations. The second audience is made up of members of the public who may or may not understand or know about their research. For example, the following passage is a summary of a paper that appears in the Public Library of Science (PLoS), an online science journal:

A systematic analysis of Alzheimer disease amyloid peptide variants in *Drosophila* brain demonstrates that their predicted propensity to form protofibrillar aggregates correlates best with toxicity.

Biologists would have no problem understanding the language in this paragraph. However, to a person who is not familiar with this type of science, it may be interpreted as gibberish. In this, lies the challenge for scientists to communicate their research in a way that the general public can understand.

The results of the study could be written in the following way so that a general reader could follow what the researchers meant:

Studies of a particular type of brain protein, called amyloid peptides, have shown that they can sometimes change into a defective form that resembles sticky clumps. These clumps may become toxic and contribute to Alzheimer's disease, a wasting disease of the brain. Researchers are examining these proteins to find out what exactly causes them to form such clumps. The studies were carried out on fruit flies, which are commonly used as animal models for genetic and biochemical studies of humans.

Communicating to the Public Through the Internet

Many scientists do a good job of presenting their work in an accessible way on the Internet. Scientists and science journalists write news articles that explain the research in everyday

language, and can show how the research relates to the reader and to their environment. For example, who would want to read an article that only talked about research that is taking place at the South Pole? An article packed with numbers, units, and percentage rates would be pretty boring to read if it were not related to other areas such the environment, people, animals, or the climate. Also, presenting such academic subjects in a readable and engaging way, allows people to understand what research is being done and why. Such general presentation of science appeals to people because it allows the reader to relate the subject to their life and experiences. For example, both the National Science Foundation (NSF) U.S Antarctic Program and the International Polar Year (IPY) 2007-2008 have websites that explain the types of research that is going on in Antarctica and the Arctic. An NSF research vessel that is taking part in the IPY 2007-2008 is shown in **Figure** 1.15.

Figure 1.15: Gentoo penguins watch the Research Vessel Laurence M. Gould in Antarctica. The Gould is one of two research vessels operated by the National Science Foundation and is taking part in the International Polar Year 2007-2008.

A **science magazine** is a publication with news, opinions and reports about science and is written for a non-expert audience. Compare this to a scientific journal, which is written by and for scientific researchers. Science magazines are read by non-scientists and scientists who want accessible information on fields outside their specialization. Articles in science magazines are sometimes republished or summarized by the general press, in newspapers, online news sites, and blogs among other media forms.

Science magazines such as *New Scientist*, shown in **Figure** 1.16, and *Scientific American*, have non-technical summaries of popular areas of research, notable discoveries, and scientific advancements in different fields of research. Science books engage the interest of many more people. So, too, do science websites and science television programming add more images

and illustrations that help tell a story. In this way, more people can become more aware of how science effects their lives and become better informed about science subjects.

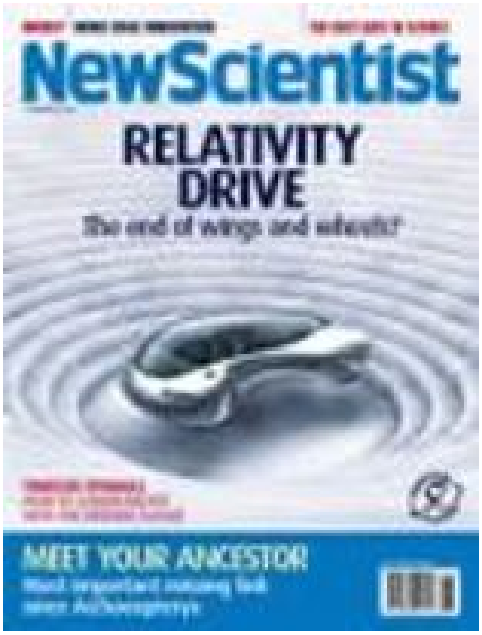

Figure 1.16: Cover of magazine.

Scientific Consensus

You may have already heard the term *scientific consensus* being used when the subject of global warming is talked about in the news. **Scientific consensus** is the collective judgment, position, and opinion of a community of scientists in a particular field of science, at a particular time. Scientific consensus is not, by itself, a scientific argument, and is not part of the "scientific method". But the topic for which a consensus exists may itself be based on both scientific arguments and scientific methods.

Consensus is normally carried out by scientists talking to each other and sharing their ideas and findings. Scientists can accomplish consensus by giving talks or presentations at conferences, or by publishing their ideas and findings for other scientists to read. This can lead to a situation where those within the field of science can recognize a consensus when it exists, but communicating that to others, such as non-scientists or the public, can be difficult. Sometimes, scientific institutes release statements that are meant to communicate a summary of the science from the inside to the outside. In cases where there is little controversy regarding the subject under study, laying out what the consensus is about can be straightforward.

Nevertheless, scientific consensus may be used in popular or political debate on subjects such as evolution or climate change that are controversial within the public sphere, but are not controversial within the scientific community.

Science and Society

Biology literally means "the study of life," and it is also a science that is very close to our everyday lives. Biology is a very broad field, covering the intricate workings of chemical processes inside our cells, to the more broad concepts of ecosystems and global climate change. Biologists study minute details of the human brain, the make up of our genes, and even the functioning of our reproductive system. For example, biologists recently finished decoding the human genome, the sequence of deoxyribonucleic acid (DNA) bases that may determine much of our abilities and predispositions for certain illnesses and can also play a major role in many court cases. For example, criminals have been caught, victims identified, and wrongly imprisoned people have been freed based on DNA evidence.

We are blitzed with headlines about possible health risks from certain foods as well as possible benefits of eating other foods. Commercials try to sell us the latest "miracle" pill for easy, fast weight loss. Many people are turning to herbal remedies to ease arthritis pain, improve memory, as well as improve their mood. Other people may choose the conventional medicines that can be bought at the pharmacist. It is important to know the effects such supplements, such as the ones shown in **Figure** 1.17, and medicines can have on the body.

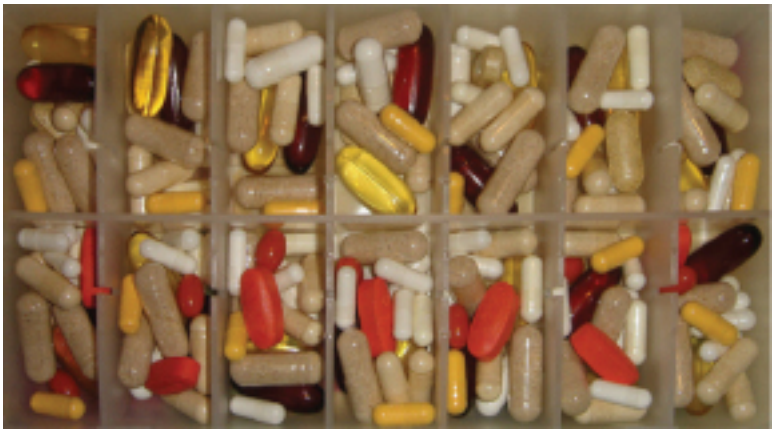

Figure 1.17: Nutritional supplements. Understanding how your body works and how nutrients work will help you decide whether you need to take a nutritional supplement. It will also help you make sense of the large amount of information available about regular medicines, if and when you need to take them.

Can a biology book give you the answers to these everyday questions? No, but it will enable you learn how to sift through the biases of investigators, the press, and others in a quest to critically evaluate the question. To be honest, five years after you are finished with this biology book, it is doubtful you would remember all the details of metabolism. However, you will have a better idea about where to look for the answer. Knowing about the process of science will also allow you to make a more informed decision. Will you be a scientist? Yes, in a way. You may not be formally trained as a scientist, but you will be able to think

critically, solve problems, have some idea about what science can and cannot do, as well as an understanding of the role of biology in your everyday life.

Biology and You

So why should you study biology? Because you are surrounded by it every day! It is about what happens in your brain as your read the words on this page and about how hippopotamuses know to come up to the surface to breath even while sleeping. Biology is about why a person with hook worms doesn't sneeze as much and about why Velcro works. From understanding the benefits of the vitamin-enriched milk or juice you that have at breakfast, to discerning commercials that promise smoother thighs or a fuller head of hair, or snack foods that announce they are the "health busy livelier option for your," you cannot be fully informed about such claims unless you understand the science behind them, or can think like a scientist to analyze them. For example, you would need to know the types of fats you need to get from your food to know why eating salmon, shown in **Figure 7** 1.18, **or other foods such as flax seeds and kiwifruit may be good for your health.**

Figure 1.18: Salmon has recently been touted as "super-brain food," but do you know why it is so good for you? Educating yourself on how science affects your life is important. It will help you analyzing the validity of such claims, help you take better care of your health, be a wiser healthcare consumer, and make you more science literate in general.

You may also become a stronger advocate for your community. For example, if a tree planting initiative has begun in your neighborhood, you can investigate the plan for your area and find out what you can do. You could then explain what the program is about to your friends and family.

Or, perhaps a city park has fallen into disrepair, and city officials are looking for feedback from the public about what to do with it. You could use scientific thinking to analyze the issue and options, and develop some solutions.

What Is a Scientist?

What exactly makes a person a "scientist" and what is their role in society? First, we should start with what scientists are not. They are not crazed geniuses with bad hair and a fondness for hysterical laughter, as **Figure a** 1.19 might suggest. Although they may not be on the cutting edge of fashion, they are regular people. They went to school like you, they studied math, reading, and science like you, and they probably exhibited at science fairs, just like the students in **Figure b** 1.19.

Figure 1.19: Spot the Scientist. (a) An example of what scientists are not. (b) Real-life young scientists at an exhibition where they are presenting their research.

Being a scientist does not require you to learn everything in this book or any other science book by heart, but understanding the important concepts really helps. Instead, being a scientist begins by *thinking* like a scientist. Scientists are curious about how the world works; they have many questions and go about answering those questions using the scientific methods, which we discussed in the *Nature of Science* lesson.

If you are fascinated by how things work and why they work a certain way, you too could become a scientist! **Research scientists** are the people that do the investigations and make the discoveries that you read or hear about. To work as a research scientist, a person usually needs an advanced degree in science. An advanced degree is obtained by attending graduate school after getting a Bachelor of Science, Engineering, or Arts degree. A Bachelor degree normally takes four years to complete; graduate degrees usually take two years for a Masters degree and four or more years to complete a Doctorate degree.

Scientific research offers much more to a person than just discovering new things. Researchers have the opportunity to meet with other people (scientists and non-scientists) who care about the same subjects that the scientists research such as cancer research, marine ecology, or human nutrition. Many researchers also teach students who will become the next generation

of scientists. Scientists have many opportunities to work with different people, explore new fields, and broaden their expertise.

Scientists are part of a community that is based on ideals of trust and freedom, and their work can have a direct effect on society. As a result, the public usually has an interest in the results of research that will directly affect them. Therefore it is important that you can understand the meaning of a science story when you read it, see it, or hear about it and become an engaged and active member of the public when making decisions involving science.

Science As a Human Endeavor

Conducting science requires part human creativity and part scientific skepticism. Researchers make new observations and develop new ideas with the aim of describing the world more accurately or completely. These observations and ideas are often based on existing theories and observations that were made by earlier scientists.

For example, the history of molecular biology, the study of molecules that make up living things, is a good example of how scientific knowledge builds on earlier knowledge.

Researchers from chemistry and physics were involved in the early investigations to discover what was responsible for heredity. Scientists in the late 19^{th} and early 20^{th} century knew that organisms inherited certain characteristics such as hair color from their parents. What we now call "genes" were then called "units of heredity." Scientists did not know exactly how these heredity units were inherited or what they were made of, however. Following the development of the Mendelian theory of heredity in the 1910s and the development of atomic theory and quantum mechanics in the 1920s, such explanations seemed within reach. Researchers from chemistry and physics turned their attention to this biological question. Still, in the 1930s and 1940s it was not clear which, if any, area of research would be most successful.

In 1940, geneticists George Beadle and Edward Tatum demonstrated a relationship between genes and proteins. In 1944, physician and researcher Oswald Avery further elaborated on that finding by demonstrating that genes are made up of DNA. In 1952, geneticist Alfred Hershey and lab assistant Martha Chase confirmed that the genetic material of a virus that infects bacteria is made up of DNA. And in 1953, biologist James Watson and biophysicist Francis Crick, with the help of X-ray crystallographer Rosalind Franklin, worked out the three dimensional structure of DNA and built a model of the double helix structure of the molecule.

There have been many additional discoveries about DNA and heredity since then, which you will learn more about in the Molecular Genetics and Biotechnology chapters.

Influences on Scientific Research

To nonscientists, the competition, frustration, cooperation, and disagreement between research scientists can seem disorganized. Scientific knowledge develops from humans trying to figure things out. Scientific research and discoveries are carried out by people—people who have virtues, values, shortcomings, and limitations—just like everyone else. As a result, science and research can be influenced by the values of the society in which the research is carried out. How do such values influence research?

This question is of interest to more than just the scientific community. Science is becoming a larger part of everyone's life, from developing more effective medicines to designing innovative sustainable air conditioning systems that are modeled after the self-cooling nests of termites. The public has become more interested in learning more about the areas of science that affect everyday life. As a result, scientists have become more accountable to a society that expects to benefit from their work.

It costs money to carry out scientific studies. Things such as the cost of equipment, transportation, rent, and salaries for the people carrying out the research all need to be considered before a study can start. The systems of financial support for scientists and their work have been important influences of the type of research and the pace of how that research is conducted. Today, funding for research comes from many different sources, some of which include:

- Government, for example, through the National Institutes of Health (NIH), Center for Disease Control and Prevention (CDC), and the Food and Drug Administration (FDA)
- Military funding (such as through the Department of Defense)
- Corporate sponsorship
- Non-profit organizations, such as the American Cancer Society, Stroke Awareness For Everyone, Inc. (SAFE)
- Private donors

When the economy of a country slows down, the amount of money available for funding research is usually reduced, because both governments and businesses try to save money by cutting out on non-essential expenses.

Many pharmaceutical companies are heavily invested in research and development, on which they spend many millions of dollars every year. The companies aim to research and develop drugs that can be marketed and sold to treat certain illnesses, such as diabetes, cancer, or high blood pressure. Areas of research in which the companies do not see any hope of a return on their huge investments are not likely to be studied.

For example, two researchers, Evangelos Michelakis and Steven Archer of the University of Alberta, Canada, recently reported that a drug that has been used for in the treatment of rare metabolic disorders could be an effective drug for the treatment of several forms of

cancer. Dichloroacetic acid, (DCA), is a chemical compound that appears to change the way cancer cells get energy, without affecting the function of normal cells. The researchers found that DCA killed cancer cells that were grown in the lab and reduced the size of tumors in rats.

However, DCA is non-patentable as a compound. A **patent** is a set of rights granted to a person or company (the patentee) for a certain period of time which allows the patentee the exclusive right to make, use, sell, or offer to sell the patented item. Because DCA cannot currently be patented, concerns are raised that without the financial security a patent would ensure, the financial incentive for the pharmaceutical industry to get involved in DCA-cancer research would be reduced, and therefore clinical trials of DCA may not be funded.

But, other sources of funding exist; previous studies of DCA have been funded by government organizations such as the National Institutes of Health (NIH), the Food and Drug Administration (FDA), the Canadian Institutes of Health Research and by private charities such as the Muscular Dystrophy Association. Recognizing the possible challenges to funding, Dr. Michelakis's lab took the unusual step of directly asking for online donations to fund the research. After six months, his lab had raised over $800,000, which was enough to fund a small clinical study. Dr. Michelakis and Dr. Archer have nonetheless applied for a patent on the use of DCA in the treatment of cancer.

Funding for research can also be influenced by the public and by social issues. An intense amount of public interest was raised by the DCA study. The story received much media attention in early 2007. As a result, the American Cancer Society and other medical organizations received a large volume of public interest and questions regarding DCA. A few months later, the Department of Medicine of Alberta University reported that after the trial funding was secured, both the Alberta local ethics committee and Health Canada approved the first DCA Clinical Trial in Cancer.

Government funding of research can be indirectly influenced by the public. Funding priorities for specific research can be influenced by the ethical beliefs or reservations of elected public officials, or influenced by the public during constitutional amendment elections. Celebrities, often campaign to bring public attention to issues that are important to them. For example, Lance Armstrong, in **Figure** 1.20, talks publicly about his experiences as a former cancer patient to help raise awareness about cancer research and the importance of funding for clinical trials.

Science and Ethics

Ethics, also called moral philosophy, is the discipline concerned with what is morally good and bad, right and wrong. The term is also applied to any system or theory of moral values or principles. Personal ethics is the moral code that a person adheres to, while social ethics includes the moral theory that is applied to groups. Bioethics is the social ethics of biology and medicine; it deals with the ethical implications of biological research and applications,

Figure 1.20: Lance Armstrong, seven-time winner of the Tour de France, visited the NIH as part of the Tour of Hope, a week-long bicycle relay across the United States to raise awareness about cancer research and the importance of clinical trials.

especially in medicine. Bioethicists are concerned with the ethical questions that arise in the relationships among biology, biotechnology, medicine, politics, law, and philosophy.

While scientific research has produced social benefits, it has also posed some troubling ethical questions. For example, when is it okay to test an experimental cancer drug on people? Developing a new drug takes a long time, maybe as much as 10 years, or more. There are many rules and regulations that drug researchers need to stick to while developing drugs to treat specific illnesses.

Generally, drugs cannot be tested on people until researchers have evidence that the drug does the job that they claim it does (in this case kills cancer cells), but also that the drug will not make patients more ill or cause death. However, if the drug has tested successfully in earlier experiments, and scientists are quite confident that the drug does help kill off cancer cells, is it ethical to allow patients with terminal cancer, who have no other treatment options, to try the experimental drug?

With new challenges in public health and health policy, and with advances in biotechnology, bioethics is a fast-growing academic and professional area of inquiry. Some recent bioethical debates also include:

Refusal of medical treatment The choice of a patient to refuse certain life-saving medical procedures such as a blood transfusion, or refusal by a parent or guardian for medical treatment for the patient.

Euthanasia The choice by a terminally ill person to have medical assistance in dying.

Stem cell research Research involving stem cells, which can be harvested from human embryos.

Animal cloning The ability and usefulness of scientists cloning animals for various needs, such as vaccine development, tissues for transplant into humans such as heart valve, and increased food production. Dolly the sheep, probably the most famous animal clone to date, is shown in **Figure** 1.21.

Figure 1.21: Dolly the sheep is seen here with one of her lambs. In 1997, Dolly was the first mammal to be cloned, and quickly became world-famous. She was euthanized in 2003 after she developed a common, but serious lung disease. To "grow" her, researchers at the Roslin Institute in Scotland, collected DNA from a mammary cell of another sheep (technically her (older) twin sister), and then injected the DNA into a stem cell which had its own DNA removed. That stem cell then developed into an embryo.

Because research may have a great effect on the wellbeing of individual people and society in general, scientists are required to behave ethically. Scientists who conduct themselves ethically treat people (called *subjects*) who are involved in their research respectfully. Subjects are not allowed to be exploited deliberately, exposed to harm, or forced to do something they do not agree to.

Science in the Media

A lot of popular science articles come from sources whose aim is to provide a certain amount of entertainment to the reader or viewer. Many popular science articles will examine how a phenomenon relates to people and to their environment. Nevertheless, there is a tendency in the popular media to dilute scientific debates into two sides, rather than cover the complexities and nuances of an issue.

Even well-intentioned scientists can sometimes unintentionally create truth-distorting media

firestorms because of journalists' difficulty in remaining critical and balanced, the media's interest in controversy, and the general tendency of science reporting to focus on apparent "groundbreaking findings" rather than on the larger context of a research field. Sometimes scientists will seek to exploit the power of the media. When scientific results are released with great fanfare and limited peer review, the media often requires skepticism and further investigation by skilled journalists and the general public.

The dichloroacetic acid (DCA) story, discussed earlier in this lesson, is an example of what can go wrong when a scientific discovery grasps the public's attention.

An intense amount of public interest was raised by the study and the story received much media attention. As a result, the American Cancer Society and other medical organizations received a large volume of public interest and questions about the "miracle cure," DCA.

One of the first stories about the findings contained the headline:

"Cheap, 'safe' drug kills most cancers"

The article did explain that the studies were only carried out on cancer cells grown in the lab and in rats. However, the headline may have given some readers the impression that human testing of DCA was complete. People were wildly interested in this new "cure" to cancer. This prompted the American Cancer Society and other organizations to issue reports that reminded people that although the study results were promising, no formal clinical trials in humans with cancer had yet been carried out. They stressed the need for caution in interpreting the early results. Doctors warned of possible problems if people attempted to try DCA outside a controlled clinical trial. The media received some criticism for the sensation that arose due to their coverage of the discovery.

Therefore, it is important to remember as a member of the public that some popular science news articles can be misleading. A reader can misinterpret the information, especially if the information has a emotional affect on the reader. Also, some articles are written by people who have limited understanding of the subject they are interpreting and can be produced by people who want to promote a particular point of view. Unfortunately, it can be difficult for the non-expert to identify misleading popular science. Sometimes, results are presented in the media without a context, or are exaggerated. Popular science may blur the boundaries between formal science and sensationalism. It is best to analyze such information with skepticism as you would if you were to make an observation in an investigation, and look at the whole context of an issue, rather than just the focus of a particular news item.

For example, in early 1999 West Nile virus, a virus most commonly found in Egypt, was accidentally introduced to New York. Although infection by the virus causes mostly mild or no symptoms in people, in rare instances, West Nile virus can cause inflammation of the brain. The illness, called West Nile Fever, spread across the continent from east to west, carried by infected birds. Mosquitoes spread the disease to mammals. Mosquito larvae (young) are shown in **Figure** 1.22.

There was intense media coverage about the spread of this disease across the United States,

and much talk about what this meant for everyone. News coverage of West Nile Fever tended to focus on the serious form of the disease, West Nile Encephalitis, which can cause harmful illness and death. The fact that there is no vaccine for the disease was also emphasized.

Figure 1.22: Mosquito larvae. As seen on the picture, larvae group together in standing water. The darker structure at the top center of the image is one pupa, another stage of the mosquito lifecycle. Mosquitoes can transfer diseases between animals, including West Nile Fever and malaria. You can avoid mosquito bites by covering your arms and legs while outside during the early morning and late evening, and by applying an insect repellant.

However, it is worthwhile considering that until October 2007 there had been a total of 26, 997 confirmed cases of West Nile virus infection, and 1,038 confirmed deaths from the disease. Compare this to the estimated 15 to 60 million people in the United States who are infected with the flu virus every year, and the estimated 36,000 people who die every year from flu complications.

So the next time you are shocked or horrified by a seemingly gloomy forecast in the media, consider how the issue fits into the bigger story.

Biotechnology: Science Applied to Life

Biotechnology is technology based on biology; it involves the use of organisms or biological processes and can be especially used in agriculture, food science, and medicine. It is the application of biological knowledge to develop tools and products that allow us to control and adapt to our environment.

Biotechnology has effected society and in a number of ways. Although it has been used for centuries in traditional production processes, such as animal breeding shown in **Figure** 1.23, crop growing, and wine making, modern biotechnology is a recent field of science. Bioengineering is the science upon which all biotechnological applications are based. New de-

velopments and new approaches are developing at a very fast pace. Biotechnology combines scientific fields such as genetics, molecular biology, biochemistry, and cell biology.

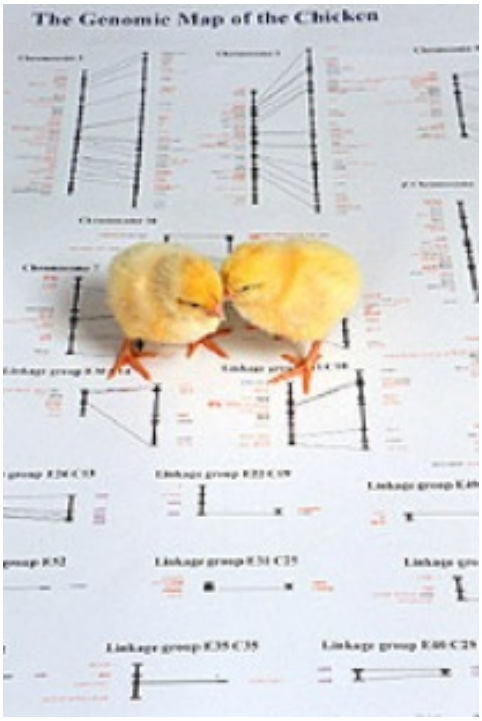

Figure 1.23: Chicks standing on a picture of a genetic map of a chicken. Mapping the genome of organisms is a major part of biotechnology.

The field of modern biotechnology is thought to have largely begun in 1980, when the United States Supreme Court ruled that a genetically-modified microorganism could be patented. Indian-born researcher, Ananda Chakrabarty, had developed a bacterium that was able to break down crude oil, which he proposed to use in treating oil spills.

Applications of Biotechnology

Biotechnology has applications in four major industrial areas, including health care, crop production and agriculture, non-food uses of crops such as biofuels, and environmental uses. One application of biotechnology uses organisms to produce things such as nutritional supplements like vitamins or amino acids, and milk products like cheese, kefir, and yogurt. Biotechnology is also used to recycle, treat waste, and clean up sites contaminated by industrial waste. The use of microorganisms to clean up contaminated sites such as an oil spill is called **bioremediation.**

Medical applications of biotechnology include designing organisms to produce medicines such as antibiotics, or other chemicals. Medical applications for people also include gene therapy

which could be used to treat a person who has a genetic disorder such as cystic fibrosis.

An example of an agricultural application is designing plants to grow under specific environmental conditions or in the presence (or absence) of certain chemicals, such as the cress shown in **Figure** 1.24. The cress plant has been genetically modified to turn red only in the presence of nitrogen dioxide, a chemical that is released by landmines and other unexploded bombs. Researchers at the Danish biotechnology company that developed the plant hope that the seeds can be spread over former battleground areas where they will grow and mark the sites of the explosives, thus speeding up the land mine removal process.

Figure 1.24: This thale cress has been genetically modified to turn red only in the presence of nitrogen dioxide, a chemical marker for landmines or other unexploded bombs. Researchers hope that the cress seeds can be spread over former battleground areas, where they will grow and mark the sites of explosives, thus lessening the risk to the people and animals who live in those areas and work to remove the explosives.

Another hope is that biotechnology might produce more environmentally friendly solutions than traditional industrial agriculture. An example of this is the engineering of a plant to express a pesticide, which cuts out the need to apply pesticides to the plants. The corn plants in **Figure** 1.25 have been genetically modified (changed) to produce a toxin that comes from a naturally occurring soil bacterium called *Bacillus thuringiensis*. The Bt toxin kills the pests that eat and destroy corn crops. Whether or not biotechnology products such as this are more environmentally friendly in the long run is a hot topic of debate.

Use of Computers in Science and Medicine

Bioinformatics is an interdisciplinary field which helps solve biological problems using computers. Lots of information is gathered from the mapping of DNA sequences and other related types of research. Bioinformatics allows scientists to gather this information, share it and to use it. It also speeds up the process of analyzing data the scientists have collected. The field may also be called computational biology. Bioinformatics plays a key role in various areas, and it is a key part of the biotechnology and the pharmaceutical industries.

Figure 1.25: People looking at a sign that explains what the genetically modified corn does. In an effort to reduce corn stem-borer infestations, corporate and public researchers came together to develop genetically modified corn varieties suitable for Kenya. The corn plants contain a gene (gene) from a naturally occurring bacterium called . The Bt gene causes the corn plants to make Bt toxin which kills the pests that feed on the plants.

Psychologists David Patterson and Hunter Hoffman of the University of Washington in Seattle developed a virtual world computer game they called "Snow World" shown in **Figure** 1.26, in an effort to reduce the pain experienced by patients undergoing burn treatment and other medical procedures. They found that people who became fully engaged in the virtual reality snow world reported 60 percent less pain. This technology offers a promising new way to manage pain. The researchers say that an interactive digital world may distract us from reality because our minds focus on just a few things at once.

Lesson Summary

- The reliability of scientific knowledge comes partly from the objectivity of scientific methods, and also from scientists discussing ideas with each other. In talking with each other, researchers must use more than just their scientific understanding of the world. They must also be able to convince other scientists of the accuracy of their ideas.
- Graphics help to illustrate ideas that would otherwise be too confusing to describe in words only.
- The peer review process aims to make authors meet the standards of their area of study, and to meet the expected standards of science in general.

Figure 1.26: A scene from the interactive "Snow World." In this virtual reality game, players can move through the snowy landscape, throw snowballs, and watch penguins waddle past them. Researchers found that playing this game can distract people from the sense of burning pain. The researchers used healthy undergraduate student volunteers in these virtual world study to determine that perception can affect pain sensation.

- Ethics is the discipline concerned with what is morally good and bad, right and wrong. Bioethics is the social ethics of biology and medicine; it deals with the ethical implications of biological research and applications, especially in medicine. Bioethicists are concerned with the ethical questions that arise in the relationships among biology, biotechnology, medicine, politics, law, and philosophy.
- Scientists need to be able to tell each other and the public about their research and the results of their research. These two groups make up two very different audiences for scientists. Presenting academic subjects in a readable and engaging way, allows the general pubic to understand what research is being done and why. Presentation of generally written science appeals to people because it allows the reader to relate the subject to their life and experiences.
- You cannot be fully informed about the scientific issues you read about unless you understand the science behind the issues, or have the ability to think like a scientist to analyze them.
- The cost of equipment, transportation, rent, and salaries for the people carrying out the research all need to be considered before a scientific study can start. The systems of financial support for scientists and their work have been important influences of the type of research and the pace of research. Today, funding for research comes from many different sources.
- Biotechnology is the application of biological knowledge to develop tools and products that allow us to control and adapt to our environment.

Review Questions

1. What is bias in scientific terms and how is it relevant to science?
2. Who do you think the ethical rules about scientific research are aimed toward? Who do they protect?
3. Investigate a science-based societal issue that affects your town, city, or state. Research literature and news reports about the issue, analyzing the data, and examine what an individual person, the community, the local government, or federal government could do about this issue. Present your finding in the form of a poster or computer slide presentation to your class.
4. Find a science article that you believe could be improved upon by adding a graph, a picture, or a drawing. Rewrite the article in your own words, and present it to your class, along with your added graphics.
5. How has biotechnology affected modern life?
6. Science and biotechnology are pursued for different purposes. Do you agree with this statement? Explain your answer.
7. Identify an ethical issue that is raised by biotechnology.
8. Identify an ethical issue that is raised by media coverage of science.
9. Why is it a good idea to study science even if you do not want to become a career scientist?
10. What are three sources of funding for scientific research?
11. How might ethics affect funding for scientific research?

Further Reading / Supplemental Links

- http://www.accessexcellence.org/
- http://www.ipy.org/
- http://www.newscientist.com/article.ns?id=dn10971
- http://response.restoration.noaa.gov/faq_topic.php?faq_topic_id=1
- http://www.milliontreesla.org/
- http://www.ctv.ca/servlet/ArticleNews/story/CTVNews/20070120/DCA_feature_070121/20070122?hub=Health
- http://www.newscientist.com/article/mg19325890.200-no-wonder-drug.html
- http://publications.nigms.nih.gov/biobeat/gallery/index.html
- http://www.cdc.gov/mmwr/preview/mmwrhtml/rr5606a1.htm
- http://publications.nigms.nih.gov/findings/sept05/bedside_sept05.html

Vocabulary

abstract A brief, usually one-paragraph, summary of the work.

academic conference A conference for researchers (not always academics) to present and

discuss their work.

animal cloning The ability and usefulness of scientists cloning animals for various needs, such as vaccine development, tissues for transplant into humans such as heart valve, and increased food production.

bioethicists People concerned with the ethical questions that arise in the relationships among biology, biotechnology, medicine, politics, law, and philosophy.

bioinformatics An interdisciplinary field which helps solve biological problems using computers; may also be called computational biology.

bioremediation The use of microorganisms to clean up contaminated sites, such as an oil spill.

biotechnology Technology based on biology; it involves the use of organisms or biological processes and can be especially used in agriculture, food science, and medicine.

conflict of interest A situation in which a researcher has professional or personal interests that are at odds with each other.

euthanasia The choice by a terminally ill person to have medical assistance in dying.

ethics The discipline concerned with what is morally good and bad, right and wrong.

peer review The process of opening a scientist's research or ideas (in the form of a scientific paper) to examination by others scientist who are experts in the same field.

reproducibility The ability to repeat experiments and get the same results.

research scientist A person that does scientific investigations and makes discoveries.

science magazine A publication with news, opinions and reports about science; written for a non-expert audience.

scientific article A scientific article discussing new research and findings; usually published in a scientific journal.

scientific consensus The collective judgment, position, and opinion of a community of scientists in a particular field of science, at a particular time.

scientific journal A publication that communicate and document the results of research carried out in universities and various other research institutions.

scientific misconduct The violation of standard codes of scholarly conduct and ethical behavior in professional scientific research.

stem cell research Research involving stem cells, usually harvested from human embryos.

systematic bias A bias that is introduced from a flaw in measurements.

Points to Consider

- Bias can also be introduced into an investigation by uncalibrated or broken equipment. Consider ways to avoid this type of bias in your investigations.
- If you had to explain to a younger student the importance of learning biology, how would you go about it?
- Rules for correct behavior in the lab include not eating or drinking, dressing correctly, and no horseplay. These rules are for general safety in the lab, but could they also be considered lab ethics?

1.3 Lesson 1.3: Tools and Techniques

Lesson Objectives

- Identify the units of measurement that scientists use.
- Contrast light microscopes and electron microscopes.
- Identify three items that are common to science labs.
- Outline the importance of mathematics to scientific research.
- Outline what students and researchers can do to stay safe while working in the lab.

Introduction

Scientists need to know they are talking the same language when it comes to measurements and analysis of data. Therefore a "standard language of measurement" called the SI system is used in scientific research. Other standard procedures and techniques are carried out so that scientists from around the world can understand what was done to get to a particular conclusion. These involve standard laboratory procedures and equipment, such as microscopes.

Units of Measurement

The measurements that scientists use are based on the **International System of Units (SI),** which is a form of the metric system. The term SI is shortened from the French term *Le Système international d'unités*. It is the world's most widely used system of units, both in science and business. It is useful to scientists because it is based on multiples of 10. The SI was developed in 1960 from an older metric system and is used in almost every country.

The SI is not static, as the technology of measurement progresses, units are created and definitions are changed through international agreement among many nations. The international system of units is made up of a seven base units, shown in **Table 2.2 ??** lists SI Base Units. From these seven base units several other units are derived.

Table 1.2: **SI Base Units**

Name	Symbol	Quantity
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	electric current
kelvin	K	thermal energy (temperature)
mole	mol	amount of substance
candela	cd	luminous intensity

A prefix may be added to SI units to make a multiple of the original unit. An **SI prefix** is a name or symbol that is put before a unit of measure (or its symbol) to form a decimal or a multiple of the unit. For example, *kilo-* is a multiple of a thousand and *milli-* is a multiple of a thousandth, so there are one thousand *millimeters* in a meter, and one thousand meters in a *kilometer*. All prefixes are multiples of 10, as you can see from **Table 2.3 ??** lists SI Prefixes. The prefixes are never combined; a millionth of a kilogram is a *milligram* not a *microkilogram*.

Table 1.3: **SI Prefixes**

Name	Symbol	Factor of 10	
tera-	T	1,000,000,000,000 (10^{12})	trillion (thousand billion)
giga-	G	1,000,000,000 (10^{9})	billion (thousand million)
mega-	M	1,000,000 (10^{6})	million
kilo-	k	1000 (10^{3})	thousand
hecto-	h	100 (10^{2})	hundred

Table 1.3: (continued)

Name	Symbol	Factor of 10	
deca-	da	10 (10^{1})	ten
deci-	d	1 (10^{-1})	tenth
centi-	c	0.1 (10^{-2})	hundredth
milli-	m	0.01 (10^{-3})	thousandth
micro-	µ	0.00001 (10^{-6})	millionth
nano-	n	0.00000001 (10^{-9})	billionth
pico-	p	0.00000000001 (10^{-12})	trillionth

The Laboratory

A laboratory is a place that has controlled conditions in which scientific research, experiments, and measurement may be carried out. Scientific laboratories can be found in schools and universities, in industry, in government facilities, and even aboard ships and spacecraft, such as the one shown in **Figure** 1.27.

Figure 1.27: Labs are not always Earth-bound, like the biochemistry lab to the left is. This astronaut is working in a lab on the International Space Station (right).

Because of the different areas of science, there are many different types of science labs that each include different scientific equipment. For example, a physics lab might contain a particle accelerator, in which the particles that make up atoms are studied. A chemistry or biology lab most likely contains a fume hood where substances with poisonous fumes can be worked. A particle accelerator and a fume hood are both shown in **Figure** 1.28. Despite the great differences among labs, some features are common in them.

Most labs have workbenches or countertops at which the scientist may sit or stand to do work comfortably. This is important because scientists can spend all day working in the lab. A scientist usually records an experiment's progress in a lab notebook, but modern labs almost always contain a computer for data collection and analysis. In many labs computers are also used for lab simulations (modeling or imitating an experiment or a natural process),

and for presenting results in the form of graphs or tables.

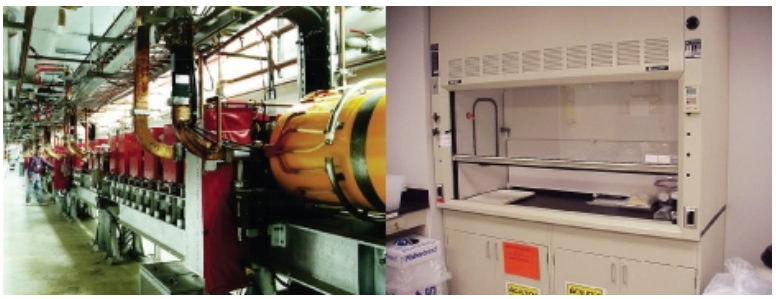

Figure 1.28: Different fields of science need different types of equipment, such as the particle accelerator at left, found in a physics lab, and the fume hood, at right, found in chemistry labs, but also sometimes in biology labs.

Lab Equipment

Lab techniques include the procedures used in science to carry out an experiment. Lab techniques follow scientific methods, and while some of them involve the use of simple laboratory equipment such as glassware (shown on the shelves in **Figure** 1.27), others use more complex and expensive equipment such as electrical and computerized machines such as the particle accelerator shown in **Figure** 1.28, or use expensive supplies.

Equipment commonly found in a biology labs include microscopes, weighing scales or balances, water baths, glassware (such as test tubes, flasks, and beakers), Bunsen burners, tongs, pipettes shown in **Figure** 1.29, chemical reagents, lab coats, goggles, and biohazard waste containers.

Figure 1.29: Pipettes are small, but important tools in many biology labs. Micropipettes, such as these here, are calibrated to measure very small amounts of liquids. For example, 100 microliters (100 µL) which is about half the volume of your little finger tip; or even 1 µL, which is smaller than a drop of water.

Light Microscopes

Microscopes are instruments used to view objects that are too small to be seen by the naked eye. Optical microscopes, such as the one shown in **Figure** 1.30, use visible light and lenses to magnify objects. They are the simplest and most widely used type of microscopes. Compound microscopes are optical microscopes which have a series of lenses, and have uses in many fields of science, particularly biology and geology. The scientist in **Figure** 1.31 is looking through a compound light microscope that is fitted with a digital camera.

Resolution is a measure of the clarity of an image; it is the minimum distance two points can be separated and still be distinguished as two separate points. Because light beams have a physical size, which is described in *wavelengths*, it is difficult to see an object that is about the same size or smaller than the wavelength of light. Objects smaller than about 0.2 micrometers appear fuzzy, and objects below that size cannot be seen.

Magnification involves enlarging the image of an object so that it appears much bigger than its actual size. Magnification also refers to the number of times an object is magnified. For example, a lens that magnifies 100X, magnifies an object 100 times larger than its actual size. Light microscopes have three objective lenses that have different magnifications, as shown in **Figure** 1.32. The ocular lens has a magnification of 10X, so a 100X objective lens and the ocular lens together will magnify an object by 1000X.

Visible light has wavelengths of 400 to 700 nanometers, which is larger than many objects of interest such as the insides of cells. Scientists use different types of microscopes in order to get better resolution and magnification of objects that are smaller than the wavelength of visible light. Objects that are to be viewed under an electron microscope may need to be specially prepared to make them suitable for magnification.

Electron Microscopes

Electron microscopes use electrons instead of photons (light), because electrons have a much shorter wavelength than photons and thus allow a researcher to see things at very high magnification, far higher than an optical microscope can possibly magnify.

There are two general types of electron microscopes: the Transmission Electron Microscope that shoots electrons through the sample and measures how the electron beam changes because it is scattered in the sample, and the Scanning Electron Microscope that scans an electron beam over the surface of an object and measures how many electrons are scattered back.

Transmission electron microscopy (TEM) is an imaging method in which a beam of electrons is passed through a specimen. An image is formed on photographic film or a fluorescent screen by the electrons that scatter when passing through the object. TEM images show the inside of the object.

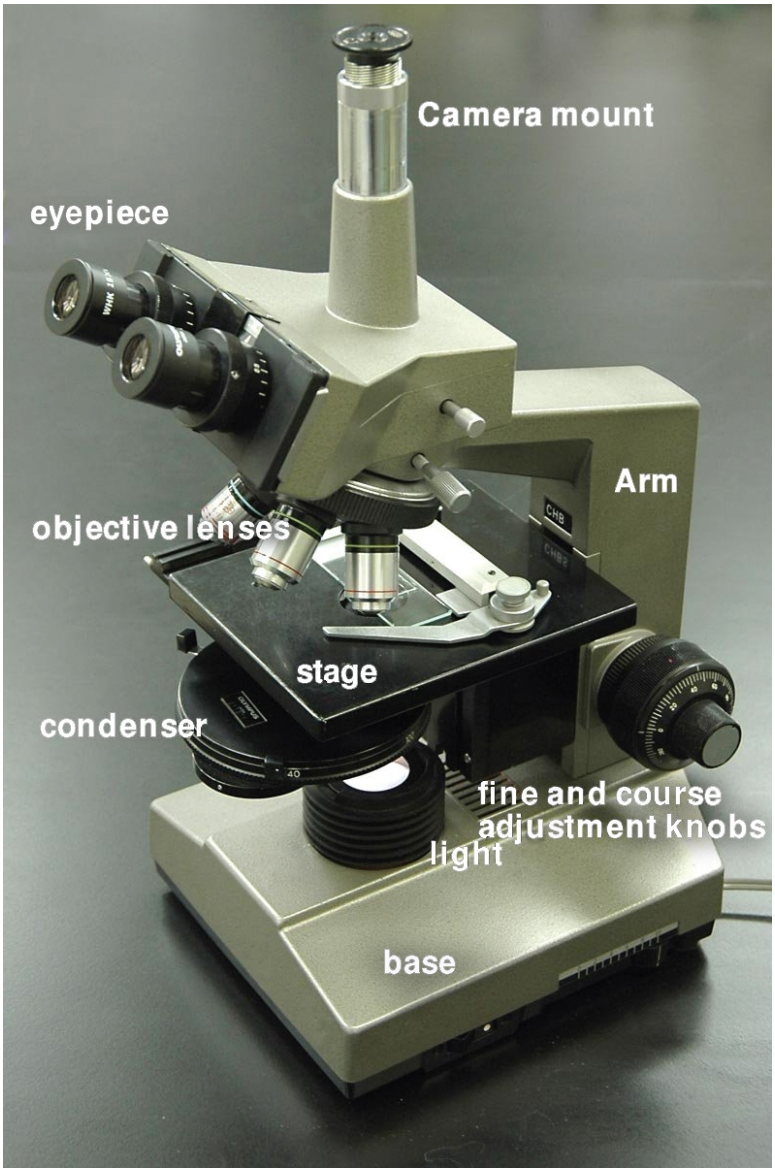

Figure 1.30: Compound light microscopes use lenses to focus light. Typical magnification of a light microscope is up to 1500x. This microscope has two optical lenses and is called a stereo microscope. The various parts of the microscope are labeled.

Figure 1.31: This scientist is using a stereo microscope, which is a light microscope with two ocular lenses (the microscope lense that is closest to the eye). The microscope is fitted with a digital imaging device that can take digital photos of what the researcher sees.

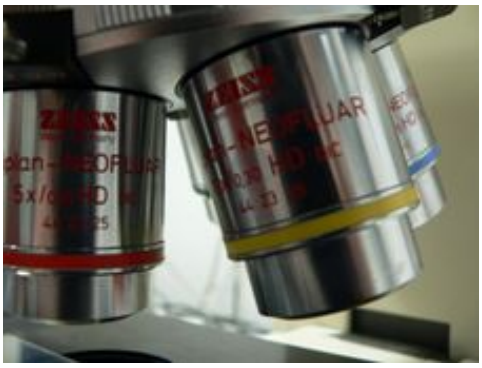

Figure 1.32: Objective lenses of a light microscope.

The **scanning electron microscope (SEM)** is a type of electron microscope capable of producing high-resolution images of a sample surface. Due to the manner in which the image is created, SEM images have a characteristic three-dimensional appearance and are useful for judging the surface structure of the sample. Sometimes objects need to be specially prepared to make them better suited for imaging under the scanning electron microscope, as shown with the insect in **Figure** 1.33.

Electron microscopes work under low pressures and usually in a vacuum chamber to avoid scattering the electrons in the gas. This makes the microscopes considerably larger and more expensive than optical microscopes. The different types of images from the two electron microscopes are shown in **Figure** 1.34.

Figure 1.33: This insect has been coated in gold, as part of the preparation for viewing with an SEM.

Aseptic Technique

In the microbiology lab, **aseptic technique** refers to the procedures that are carried out under sterile conditions. Scientists who study microbes are called microbiologists. Microbiologists must carry out their lab work using the aseptic technique to prevent microbial contamination of themselves, contamination of the environment they are working in, including work surfaces or equipment, and contamination of the sample they are working on. Bacteria live on just about every surface on Earth, so if a scientist wants to grow a particular type of bacterium in the lab, he or she needs to be able to sterilize their equipment to prevent contamination by other bacteria or microorganisms. The aseptic technique is also used in medicine, where it is important to keep the human body free of contamination.

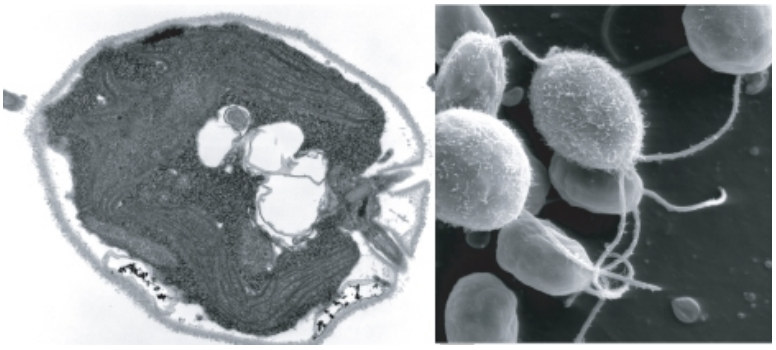

Figure 1.34: SEM and TEM images of the algae . The SEM image, shown at the right, is a three-dimensional image of the surface of the organism, whereas the TEM image is a two-dimensional image of the interior of the organism.

Aseptic technique is used whenever bacteria or other microbes are transferred between nutrient media or in the preparation of the nutrient media. Some equipment that is used in the aseptic technique include a Bunsen burner, an autoclave (**Figure** 1.35), hand and surface sanitizers, neoprene gloves, and a fume hood.

Students of microbiology are taught the principles of aseptic technique by hands-on laboratory practice. Practice is essential in learning how to handle the lab tools without contaminating them.

Scientific Models

Scientific models are representations of reality. To describe particular parts of a phenomenon, or the interactions among a set of phenomena, it is sometimes helpful to develop a model of the phenomenon. For instance, a scale model of a house or of a solar system is clearly not an actual house or an actual solar system; the parts of an actual house or an actual solar system represented by a scale model are, only in limited ways, representative of the actual objects.

Scientific modeling is the process of making abstract models of natural phenomena. An **abstract model** is a theoretical construct that represents something. Models are developed to allow reasoning within a simplified framework that is similar to the phenomena being investigated. The simplified model may assume certain things that are known to be incomplete in some details. Such assumptions can be useful in that they simplify the model, while at the same time, allowing the development of acceptably accurate solutions. These models play an important role in developing scientific theories.

A **simulation** is a model that runs over time. A simulation brings a model to life and shows how a particular object or phenomenon will behave. It is useful for testing, analysis or training where real-world systems or concepts can be represented by a model. For the

Figure 1.35: A worktop autoclave. Autoclaves commonly use steam heated to 121°C (250°F), at 103 kPa (15 psi) above atmospheric pressure. Solid surfaces are effectively sterilized when heated to this temperature. Liquids can also be sterilized by this process, though additional time is required to reach sterilizing temperature.

Figure 1.36: A model of planets of the solar system. This model is clearly not a real solar system; it is a representation of the planets Jupiter, Saturn, Neptune, and Uranus. Scientists use representations of natural things to learn more about them. Also, the visitors to the Griffith Observatory in Los Angeles can get a better idea of the relative sizes of the planets (and Pluto!) by observing this model.

scientist, a model also provides a way for calculations to be expanded to explore what might happen in different situations. This method often takes the form of models that can be programmed into computers. The scientist controls the basic assumptions about the variables in the model, and the computer runs the simulation, eventually coming to a complicated answer.

Examples of models include:

- Computer models
- Weather forecast models
- Molecular models
- Climate models
- Ecosystem models
- Geologic models

One of the main aims of scientific modeling is to allow researchers to quantify their observations about the world. In this way, researchers hope to see new things that may have escaped the notice of other researchers. There are many techniques that model builders use which allow us to discover things about a phenomenon that may not be obvious to everyone.

- The National Weather Service Enhanced Radar Images web site (http://radar.weather.gov/) is an excellent example of a simulation. The site exhibits current weather forecasts across the United States.

Evaluating Models

A person who builds a model must be able to recognize whether a model reflects reality. They must also be able to identify and work with differences between actual data and theory.

A model is evaluated mostly by how it reflects past observations of the phenomenon. Any model that is not consistent with reproducible observations must be modified or rejected. However, a fit to observed data alone is not enough for a model to be accepted as valid. Other factors important in evaluating a model include:

- Its ability to explain past observations
- Its ability to predict future observations
- Its ability to control events
- The cost of its use, especially when used with other models
- Ease of use and how it looks

Some examples of the different types of models that are used by science are shown in **Figures** 1.37 and 1.38.

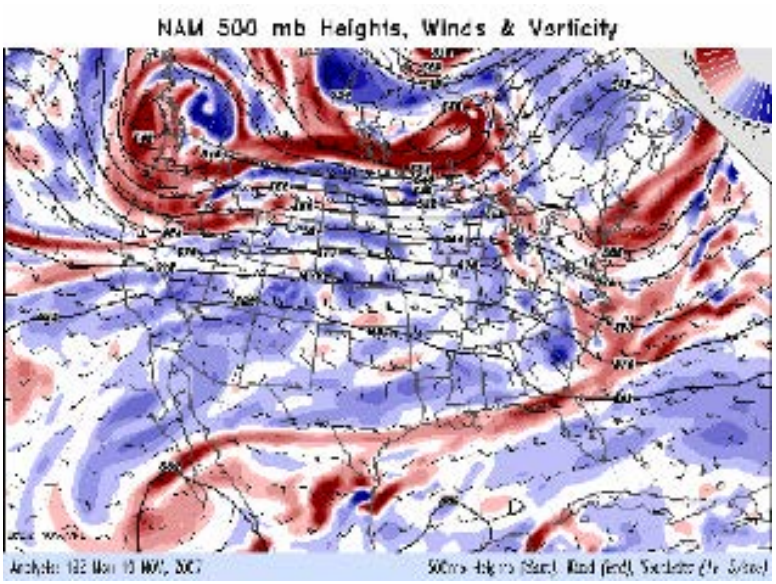

Figure 1.37: A computer model of wind patterns across the continental United States for 19 November, 2007. This model is used to forecast wind speeds and directions. Data on wind speed, direction, and related data are entered into a computer which then produces this simulation. This visual model is much easier for a person to understand than a large table of numbers.

Figure 1.38: Biosphere 2 is an example of a very large three-dimensional model which biologists built to attempt to recreate a self-sustaining biome. To learn more about biomes and ecosystems, go to the chapter.

Theories as "Models"

Theories are constructed in order to explain, predict and understand phenomena. This could include the movement of planets, weather patterns, or the behavior of animals, for example. In many instances we are constructing models of reality. A theory makes generalizations about observations and is made up of a related set of ideas and models. The important difference between theories and models is that the first is explanatory as well as descriptive, while the second is only descriptive and predictive in a much more limited sense.

Lab Safety

In some laboratories, conditions are no more dangerous than in any other room. In many labs, though, additional hazards are present. Laboratory hazards are as varied as the subjects of study in laboratories, and might include poisons, infectious agents, flammable, explosive, or radioactive materials, moving machinery, extreme temperatures, or high voltage. The hazard symbols for corrosive, explosive, and flammable substances are shown in **Figure** 1.39. In laboratories where conditions might be dangerous, safety precautions are important. Lab safety rules minimize a person's risk of getting hurt, and safety equipment is used to protect the lab user from injury or to help in responding to an emergency.

Figure 1.39: The hazard symbols for corrosive, explosive, and flammable substances.

Some safety equipment that you might find in a biology lab includes:

Sharps Container A container that is filled with used medical needles and other sharp instruments such as blades, shown in **Figure** 1.40. Needles or other sharp items that have been used are dropped into the container without touching the outside of the container. Objects should never be pushed or forced into the container, as damage to the container or injuries may result.

Laminar Flow Cabinet A carefully enclosed bench designed to prevent contamination of biological samples. Air is drawn through a fine filter and blown in a very smooth, laminar (streamlined) flow towards the user. The cabinet is usually made of stainless steel with no gaps or joints where microorganisms might collect.

Gloves Due to possible allergic reactions to latex, latex gloves are not recommended for lab

Figure 1.40: Immediate disposal of used needles, and other sharp equipment into a sharps container is standard procedure.

use. Instead, vinyl or nitrile gloves, shown in **Figure** 1.41, are often used. Gloves protect the wearers hands and skin from getting contaminated by microorganisms or stained or irritated by chemicals.

Figure 1.41: A nitrile glove. Latex gloves are no longer recommended so vinyl gloves or nitrile gloves, which are usually green or blue in color, are preferred.

Lab Coat A knee-length overcoat that is usually worn while working in the lab. The coat helps to protect the researcher's clothes from splashes or contamination. The garment is

made from white cotton or linen to allow it to be washed at high temperature and make it easy to see if it is clean.

Safe Laboratory Practice

Safety precautions are in place to help prevent accidents. Always wear personal protective equipment such as goggles and gloves when recommended to do so by your teacher.

- Tell your teacher immediately if an accident happens.
- The production of aerosols due to poor technique such as squirting the last drop out of pipettes, and the spread of contamination due to spills is completely avoidable and especially important if you are handling infectious material or chemicals.
- Wear enclosed toe shoes, instead of sandals or flip flops, or thongs. Your feet and toes could easily get hurt or broken or if you dropped something. (**Figure** 1.42)
- Do not wear loose, floppy clothes in the lab; they can get caught in or knock over equipment, causing an accident.
- If you have long hair, tie it up for the same reasons listed above.
- Do not eat or drink in the lab.
- Do not use cell phones in the lab, even if you are only sending a text message. You can easily contaminate your phone with whatever you have been working with. Consider where your hands have been, and where your face will be the next time you talk on the phone.
- Sweep up broken glass immediately and dispose in a designated area or container, or notify your teacher.
- Always listen carefully to your teacher's instructions.

Figure 1.42: Although they may be comfy and casual, flip-flops and other open-toed shoes are not suitable footwear in the lab.

Accidents

In the case of an accident, it is important to begin by telling your teacher and to know where to find safety equipment.

Some common safety equipment in a school lab:

- Fire Extinguishers
- Fire Blanket
- Eye-Wash Fountain (**Figure** 1.43)
- First-Aid Kit

Figure 1.43: Symbol for the eyewash fountain.

Through the first three lessons, we have discussed what science is and how science is done. Now we need to turn our attention to Biology. Biology is the study of life. As the 'study of life,' a knowledge of biology is an extremely important aspect of your education. Biology includes the identification and analysis of characteristics common to all living organisms. What is known about biology is discovered or identified through the same processes as all other sciences, including the scientific method and peer review process.

Lesson Summary

- The measurements that scientists use are based on the International System of Units (SI), which is form of the metric system. Based on multiples of ten, It is the world's most widely used system of units, both in science and business.
- One important use for mathematics in science is the role it plays in expressing scientific models. Statistics allow scientists to assess the reliability and range of differences in experimental results.

- Light microscopes use visible light and lenses to magnify objects. They are the simplest and most widely used type of microscopes. Electron microscopes use electrons instead of photons (light), because electrons have a much shorter wavelength than photons and therefore allow a researcher to see things at very high magnification, that greatly exceeds what an optical microscope can possibly magnify. Electron microscopes are larger and more expensive than light microscopes.
- Equipment commonly found in a biology labs include microscopes, weighing scales or balances, water baths, glassware (such as test tubes, flasks, and beakers), Bunsen burners, tongs, pipettes, chemical reagents, lab coats, goggles, and biohazard waste containers.
- Always wear personal protective equipment such as goggles and gloves, wear enclosed shoes, and do not eat or drink in the lab.

Review Questions

1. Which one of the following units of measurement would be the most appropriate in determining the mass of a banana? Kilograms, micrograms, or grams.
2. Identify the type of microscope that is most common in laboratories.
3. Contrast microscope magnification and resolution.
4. If an objective lens magnifies an object by 45×, and the optical lens magnifies by 10×. By how much will the object be magnified to the viewer?
5. Which object is larger? An object with a diameter of 1500 micrometers (µm) or an object with a diameter of 15 millimeters (mm)?
6. Why is it important that scientists use common units of measurement?
7. Name three pieces of safety equipment that you should wear while carrying out an investigation in the lab.
8. What should you first do if an accident happens in the lab?
9. If you saw this hazard sign on a chemical container, what do you think it might mean?

10. How are computer models similar to the real world, and how do they differ?

Further Reading / Supplemental Links

- http://www.chem.unl.edu/safety/hslabcon.html
- http://en.wikibooks.org/wiki/Nanotechnology/Electron_microscopy

Vocabulary

aseptic technique Laboratory procedures that are carried out under sterile conditions.

compound microscope An optical microscopes that has a series of lenses, and have uses in many fields of science, particularly biology and geology.

electron microscope A microscope that uses electrons instead of light; allow a researcher to see things at very high magnification, far higher than an optical microscope can possibly magnify.

International System of Units (SI) The measurements that scientists use; a form of the metric system.

lab coat A knee-length overcoat that is usually worn while working in the lab; helps to protect the researcher's clothes from splashes or contamination.

laboratory A place that has controlled conditions in which scientific research, experiments, and measurement may be carried out.

lab techniques The procedures used in science to carry out an experiment.

magnification Enlarging an image of an object so that it appears much bigger than its actual size; also refers to the number of times an object is magnified.

microscopes Instruments used to view objects that are too small to be seen by the naked eye.

model A physical, mathematical, or logical representation of a system, phenomenon, or process; allow scientists to investigate a phenomenon in a controlled way.

optical microscope A microscope that uses visible light and lenses to magnify objects.

resolution A measure of the clarity of an image; it is the minimum distance two points can be separated and still be distinguished as two separate points.

scanning electron microscope (SEM) Electron microscope that scans an electron beam over the surface of an object and measures how many electrons are scattered back.

scientific modeling The process of making abstract models of natural phenomena.

simulation A model that runs over time; brings a model to life and shows how a particular object or phenomenon will behave.

stereo microscope A light microscope with two ocular lenses.

transmission electron microscope (TEM) Electron microscope that shoots electrons through the sample and measures how the electron beam changes because it is scattered in the sample.

Points to Consider

- Consider how much more difficult it would be to carry out investigations without the use of computers, and the types of models that have developed due to the development of computers.
- Consider reasons why eating and drinking are not allowed in the lab.
- What additional ethical considerations would there be if you were working with living organisms in the lab, such as mice, rats, or other mammals?

1.4 Lesson 1.4: Principles of Biology

Lesson Objectives

- List some of the different areas of study in biology.
- Identify the seven characteristics of living things.
- Identify the four unifying principles of modern biology.
- List two different types of interactions that organisms can have with each other.
- Outline the formation of modern evolutionary theory.

Introduction: Characteristics of Life

Biology examines the structure, function, growth, origin, evolution, and distribution of living things. It classifies and describes organisms, their functions, how species come into existence, and the interactions they have with each other and with the natural environment. Four unifying principles form the foundation of modern biology: cell theory, evolution, genetics and homeostasis.

Most biological sciences are specialized areas of study. Biology includes biochemistry, cell biology, microbiology, immunology, genetics, physiology, zoology, ecology, evolutionary biology, and botany. Biochemistry is the study of the chemicals that make up life. Cell biology is the study of life at the level of the cell. Microbiology is the study of microscopic organisms. Immunology is the study of an organism's resistance to disease. Genetics is the study of how organisms pass traits to their offspring. The study of how the human body works is called physiology. Zoology is the study of animals. The study of how organisms interact with their environment and each other is called ecology. Evolutionary biology is the study of how populations and species change over time. Botany is the study of plants. The four unifying principles are important foundations for each and every field of biology. Applied fields of biology such as medicine and genetic research involve many specialized areas of study.

What is Life?

Not all scientists agree exactly about what makes up life. Many characteristics describe most living things. However, with most of the characteristics listed below we can think of one or more examples that would seem to break the rule, with something non-living being classified as living or something living classified as non-living.

There is not just one distinguishing feature that separates a living thing from a non-living thing. A cat moves but so does a car. A tree grows bigger, but so does a cloud. A cell has structure, but so does a crystal. Biologists define life by listing characteristics that living things share. Something that has all of the characteristics of life is considered to be alive. The duck decoy in **Figure** 1.44 may look like a duck, act like a duck in that it floats about, but it is not alive. The decoy cannot reproduce offspring, respond to its environment, or breathe.

Figure 1.44: Is it a duck? Both of these objects move across the water's surface. But, how can you tell which one is alive and which is not? You can tell by seeing which of them have all of the characteristics of life.

An individual living creature is called an **organism**. There are many characteristics that living organisms share. They all:

- respond to their environment

- grow and change
- reproduce and have offspring
- have a complex chemistry
- maintain homeostasis
- are built of structures called cells
- pass their traits onto their offspring

Responding to the Environment

If you step on a rock, it will just lie there, but if you step on a turtle, it may move or even snap at you. Living things know what is going on around them, and respond to changes in the environment. An **adaptation** refers to the process of becoming adjusted to an environment. Adaptations may include structural, physiological, or behavioral traits that improve an organism's likelihood of survival, and thus, reproduction.

Growth and Change

A seed may look like a pebble, but under the right conditions it will sprout and form a seedling that will grow into a larger plant. The pebble of course will not grow.

Reproduction

Living things make more organisms like themselves. Whether the organism is a rabbit, or a tree, or a bacterium, life will create more life.

Have Complex Chemistry

A flower has a complicated and beautiful structure. So does a crystal. But if you look closely at the crystal, you see no change. The flower, on the other hand, is transporting water through its petals, producing pigment molecules, breaking down sugar for energy, and undergoing a large number of other chemical reactions that are needed for living organisms to stay alive. We call the sum of the chemical reactions in a cell its **metabolism**.

Maintain Homeostasis

A human body has a temperature of 37° Celsius, (about 98.6° Fahrenheit). If you step outside on a cold morning, the temperature might be below freezing. Nevertheless, you do not become an ice cube. Your shiver and move your arms and legs about to stay warm. Eating food also gives your body the energy to keep warm. Living organisms keep their

internal environments within a certain range (they maintain a stable internal condition), despite changes in their external environment. This process is called **homeostasis**.

Built of Cells

If you look closely at any organism you can see that it is made of structures called **cells**. Organisms that are very different such as ferns, and fish, and elephants all look very similar at the cellular level. All living organisms are made of one or more cells. Organisms are organized in the microscopic level from atoms up to cells. The matter is structured in an ordered way. Atoms are arranged into molecules, then into macromolecules, which make up organelles, which work together to form cells. Beyond this, cells are organized in higher levels to form entire multicellular organisms, as shown in **Figure** 1.45. Cells together form tissues, which make up organs, which are part of organ systems, which work together to form an entire organism. Of course, beyond this, organisms form populations which make up parts of an ecosystem. All of Earth's ecosystems together form the diverse environment that is Earth.

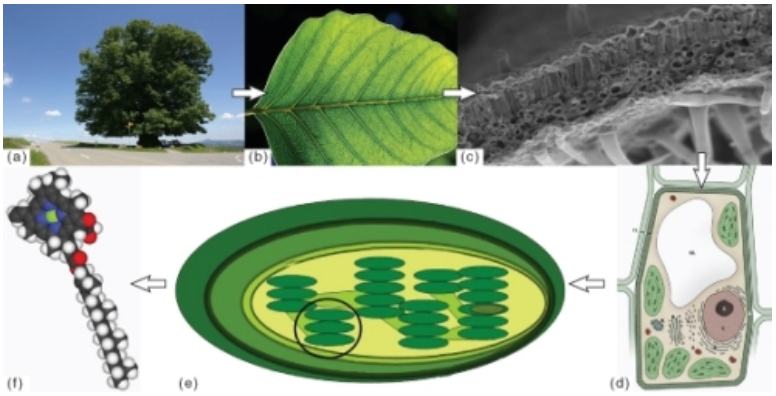

Figure 1.45: Levels of organization in a tree. (a)The tree is the organism; (b) a leaf is an organ, (c) a leaf tissue is made up of different types of cells; (d) a plant cell; (e) chloroplast is an organelle inside a plant cell; (f) chlorophyll is the photosynthetic molecule that is found in chloroplasts.

Unifying Principles of Biology

There are four unifying principles of biology that are important for types of biology studies. These are:

The Cell Theory

The cell is the basic unit of life. The Cell Theory states that all living things are made of one or more cells, or the secretions of those cells, such as the organisms shown in **Figure** 1.46. For example, shell and bone are built by cells from substances that they secrete into their surroundings. Cells come from cells that already exist, that is, they do not suddenly appear from nowhere. In organisms that are made of many cells (called multicellular organisms), every cell in the organism's body derives from the single cell that results from a fertilized egg. You will learn more about cells and the Cell Theory in the *Cell Structure and Function* chapter.

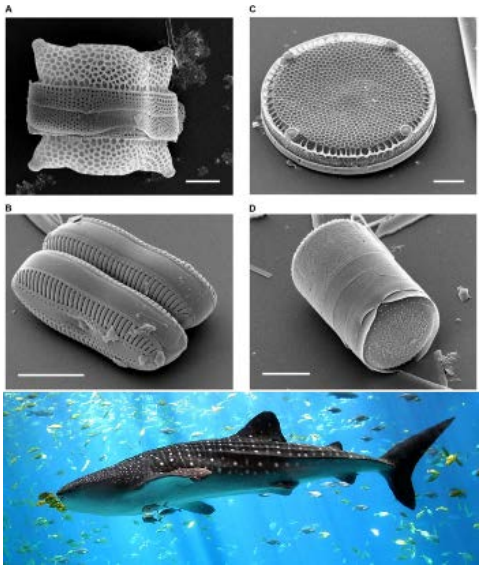

Figure 1.46: Tiny diatoms and whale sharks are all made of cells. Diatoms are about 20 µm in diameter and are made up of one cell, whereas whale sharks can measure up to 12 meters in length, and are made up of billions of cells.

Gene Theory

A living organism's traits are encoded in their DNA, the large molecule, or macromolecule, that holds the instructions needed to build cells and organisms. DNA makes up the genes of an organism. Traits are passed on from one generation to the next by way of these genes. Information for how the organism appears and how its cells work come from the organism's genes. Although the appearance and cell function of the organism may change due to the organism's environment, the environment does not change its genes. The only way that genes can change in response to a particular environment is through the process of evolution in populations of organisms. You will learn more about DNA and genes in the *Molecular Genetics* chapter.

Homeostasis

Homeostasis is the ability of an organism to control its body functions in order to uphold a stable internal environment even when its external environment changes. All living organisms perform homeostasis. For example, cells maintain a stable internal acidity (pH); and warm-blooded animals maintain a constant body temperature. You will learn more about homeostasis in *The Human Body* chapter.

Homeostasis is a term that is also used when talking about the environment. For example, the atmospheric concentration of carbon dioxide on Earth has been regulated by the concentration of plant life on Earth because plants remove more carbon dioxide from the atmosphere during the daylight hours than they emit to the atmosphere at night.

Evolution

Evolution by natural selection, is the theory that maintains that a population's inherited traits change over time, and that all known organisms have a common origin. Evolutionary theory can explain how specialized features, such as the geckos sticky foot pads shown in **Figure** 1.47, develop in different species. You will learn more about evolution in the *Evolutionary Theory* and *Evolution in Populations* chapters.

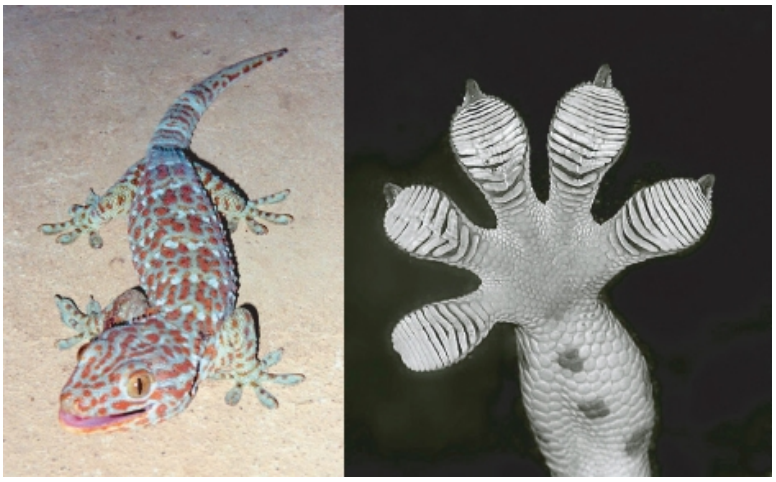

Figure 1.47: A Tokay Gecko. The pads at the tip of the Tokay gecko's foot are covered in microscopic hairs, each split into hundreds of tips that measure about 200 nanometers in diameter. By using these tiny hairs that can cling to smooth surfaces, the geckos are able to support their entire body weight while climbing walls, definately a product of evolution.

Interdependence of Living Things

Biological interactions are the interactions between different organisms in an environment. In the natural world no organism is cut off from its surroundings. Organisms are a part of their environment which is rich in living and non-living elements that interact with each other in some way. The interactions of an organism with its environment are vital to its survival, and the functioning of the ecosystem as a whole.

These relationships can be categorized into many different classes. The interactions between two species do not necessarily need to be through direct contact. Due to the connected nature of ecosystems, species may affect each other through such relationships involving shared resources or common enemies.

The term **symbiosis** comes from a Greek word that means "living together." Symbiosis can be used to describe various types of close relationships between organisms of different species, such as **mutualism** and **commensalism**, which are relationships in which neither organism is harmed. Sometimes the term symbiosis is used only for cases where both organisms benefit, sometimes it is used more generally to describe all kinds of close relationships, even when one organism is killed by another, as shown in **Figure** 1.48. Symbiosis can also be used to describe relationships where one organism lives on or in another, called **parasitism**, or when one organism kills and eats another organism, called **predation**.

Competition

Competition is as an interaction between organisms or species, for the same resources such as water, food, or hunting grounds in an environment, shown in **Figure** 1.49. Eventually, the species that is less able to compete for resources will either adapt or die out. According to evolutionary theory, competition for resources plays an important role in natural selection.

Animals that eat decomposing organic material also have an important interaction with the environment. They help to decompose dead matter and assist with the recycling of nutrients. By burying and eating dung, dung beetles, such as the one shown in **Figure** 1.50, improve nutrient cycling and soil structure. They make the dead organic matter available to bacteria that break it down even further.

Levels of Organization

In studying how organisms interact with each other, biologists often find it helpful to classify the organisms and interactions into levels of organization. Similar to the way an organism itself has different levels of organization, the ways in which organisms interact with their environment and each other can also be divided in to levels of organization. For example:

The **biosphere** includes all living things within all of their environments. It includes every

Figure 1.48: There are many different types of symbiotic interactions between organisms. Clockwise from top left: bacteria live inside your intestines in a mutualistic relationship; the bacteria produce Vitamin K for you, and they get their food from what you eat. Lions are predators that feed on other organisms such as this Cape buffalo. Similar to the E. , this bee has a mutualistic relationship with the flower, the bee feeds from the flower, and the flower gets pollinated by the bee. Clownfish that live among the tentacles of sea anemones protect the anemone from anemone-eating fish, and in turn the stinging tentacles of the anemone protect the clownfish from its predators (a special mucus on the clownfish protects it from the stinging tentacles).

Figure 1.49: Competition between organisms and species. These male deer are competing for females during rutting (mating) season. Trees in this Bangladesh forest are in competition for light.

Figure 1.50: Dung beetles have important interactions with the environment, through which many other organisms benefit.

place that life occurs, from the upper reaches of the atmosphere to the top few meters of soil, to the bottoms of the oceans. An **ecosystem** is made up of the relationships among smaller groups of organisms with each other, and their environment. Scientists often speak of the interrelatedness of living things, because, according to evolutionary theory, organisms adapt to their environment, and they must also adapt to other organisms in that environment.

A **community** is made up of the relationships between groups of different species. For example, the desert communities consist of rabbits, coyotes, snakes, birds, mice and such plants as sahuaro cactus, ocotillo, and creosote bush. Community structure can be disturbed by such dynamics as fire, human activity, and over-population.

It is thus possible to study biology at many levels, from collections of organisms or communities, to the inner workings of a cell (organelle). To learn more about the interactions of organisms, you will read the *Biomes, Ecosystems and Communities* and *Populations* chapters.

The Diversity of Life

Evolutionary theory and the cell theory give us the basis for how and why, living things relate to each other. The diversity of life found on Earth today is the result of 4 billion years of evolution. Some of this diversity is shown in **Figure** 1.51. The origin of life is not completely understood by science, though limited evidence suggests that life may already have been well-established a few 100 million years after Earth formed. Until approximately 600 million years ago, all life was made up of single-celled organisms.

The level of biodiversity found in the fossil record suggests that the last few million years include the period of greatest biodiversity in the Earth's history. However, not all scientists support this view, since there is a lot of uncertainty as to how strongly the fossil record is biased by the greater availability and preservation of more recent fossil-containing rock layers. Some researchers argue that modern biodiversity is not much different from biodiversity 300 million years ago. Estimates of the present global species diversity vary from 2 million to 100 million species, with a best estimate of somewhere near 10 million species. All living organisms are classified into one of the six kingdoms: Archaebacteria (Archaea), Eubacteria (Bacteria), Protista (Protists), Fungi, Plantae (Plants), and Animalia (Animals).

New species are regularly discovered and many, though already discovered, are not yet classified. One estimate states that about 40 percent of freshwater fish from South America are not yet classified. Every year, scientists discover the existence of many hundreds more archaea and bacteria than were previously known about. Just a few of the many members of the animal kingdom are shown in **Figure** 1.51. The animal kingdom is just a tiny portion of the total diversity of life. To learn more about the diversity of living creatures, you will read the *Classification; Prokaryotes and Viruses; Protists; Fungi; Evolution and Classification of Plants; and Introduction to Animals and Invertebrates* chapters.

Evolution of Life

Evolution is the process by which populations of organisms change over time. These organisms acquire and pass on new traits from generation to the next generation. Its occurrence over large stretches of time explains the origin of new species and the great diversity of the biological world. **Extant** species are related to each other through common descent, and products of evolution over billions of years. Analysis of the DNA of different organisms indicate there is a similarity in the DNA genetic codes that help make proteins and other molecules in very different organisms. These genetic codes are used by all known forms of life on Earth, and are very similar. The theory of evolution suggests that the genetic code was established very early in the history of life and some studies suggest it was established soon after the formation of Earth. The timeline of the evolution of life, shown in **Figure** 1.52, outlines the major events in the development of life.

How do scientists know Earth is so old? The answer is in the rocks. Contained in rocks that were once molten, shown in **Figure** 1.53, are chemical elements that act like an atomic clock. The atoms of different forms of elements (called isotopes) break down at different rates over time. Parent isotopes within these rocks decay at a predictable rate to form daughter isotopes. By determining the relative amounts of parent and daughter isotopes, the age of these rocks can be calculated—forming the so-called atomic clock.

Thus, the results of studies of rock layers (stratigraphy), and of fossils (paleontology), along with the ages of certain rocks as measured by atomic clocks (geochronology), indicate that the Earth is over 4.5 billion years old, with the oldest known rocks being 3.96 billion years

Figure 1.51: Animal diversity. This figure shows just a fraction of the diversity of life. The diversity of organisms found in the five kingdoms of life, dwarf the number of organisms found in the animal kingdom. The other kingdoms of life are Eubacteria, Archaebacteria, Protista, Fungi, and Plantae.

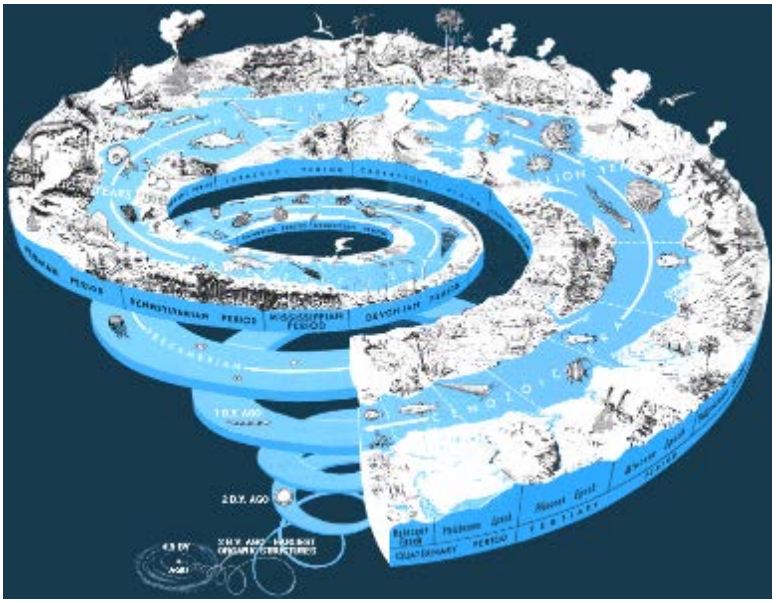

Figure 1.52: According to recent estimates, the Earth is about 4.5 billion years old. Most of the evidence for an ancient Earth is contained in the rocks that form the Earth's crust. The rock layers themselves, like pages in thick history book, record the surface shaping events of the past. Buried within them are traces of life, including the plants and animals that evolved from organic structures that existed perhaps as many as 3 billion years ago.

old. To learn more about the history of life on Earth, you will read the History of Life chapter.

Figure 1.53: Molten rock, called , is expelled by a volcano during an eruption. The lava will eventually cool to become solid rock. When first expelled from a volcanic vent, it is a liquid at temperatures from 700 °C to 1,200 °C (1,300 °F to 2,200 °F). Not all types of rocks come from cooled lava, but many do. Additional images/videos of volcanic eruptions can be seen at Hawaii Volcanic Eruption with Lightning and USGS Kilauea Volcano (and

History of Evolutionary Thought

The theory of evolution by natural selection was proposed at about the same time by both Charles Darwin and Alfred Russel Wallace, shown in **Figure** 1.54, and was set out in detail in Darwin's 1859 book *On the Origin of Species*. **Natural selection** is a process that causes heritable traits that are helpful for survival and reproduction to become more common, and harmful traits, or traits that are not helpful or advantageous for survival to become more rare in a population of organisms. This occurs because organisms with advantageous traits are more "fit" to survive in a particular environment and have "adapted" to the conditions of that environment. These individuals will have greater reproductive success than organisms less fit for survival in the environment. This will lead to an increase in the number of organisms with the advantageous trait(s) over time. Over many generations, adaptations occur through a combination of successive, small, random changes in traits, and natural selection of those variants best-suited for their environment. Natural selection is one of the cornerstones of modern biology.

The theory of evolution encountered initial resistance from religious authorities who believed humans were divinely set apart from the animal kingdom. There was considerable concern about Darwin's proposal of an entirely scientific explanation for the origin of humans. Many people found such an explanation to be in direct conflict with their religious beliefs. A caricature of Darwin as a monkey, shown in **Figure** 1.55, reflects the controversy that arose over evolutionary theory. In the 1930s, Darwinian natural selection was combined with Mendelian inheritance to form the basis of modern evolutionary theory.

Figure 1.54: Charles Darwin, left (1809-1882), and Alfred Russel Wallace, right (1823-1913). Both scientists proposed a process of evolution by natural selection at about the same time. However, Darwin was first to publish his findings.

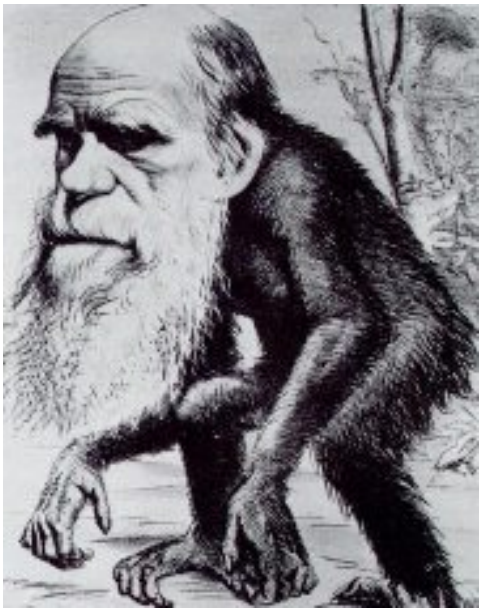

Figure 1.55: An 1871 caricature portraying Darwin with an ape body and the bushy beard he grew in 1866. Such satire reflected the cultural backlash against evolution.

The identification of DNA as the genetic material by Oswald Avery and colleagues in the 1940s, as well as the publication of the structure of DNA by James Watson and Francis Crick in 1953, demonstrated the physical basis for inheritance. Since then, genetics and molecular biology have become core aspects of evolutionary biology.

Currently the study of evolutionary biology involves scientists from fields as diverse as biochemistry, ecology, genetics and physiology, and evolutionary concepts are used in even more distant disciplines such as psychology, medicine, philosophy and computer science.

Misconceptions About Evolution

The following list includes some common misconceptions about evolution.

- The term evolution describes the changes that occur in populations of living organisms over time. Describing these changes does not address the origin of life. The two are commonly and mistakenly confused. Biological evolution likewise says nothing about cosmology, the Big Bang, or where the universe, galaxy, solar system, or Earth came from.
- Humans did not evolve from chimpanzees or any other modern ape; instead they share a common ancestor that existed around 7 million years ago.
- The process of evolution is not necessarily slow. Millions of years are not required to see evolution in action. Indeed, it has been observed multiple times under both controlled laboratory conditions and in nature.
- Evolution is not a progression from "lower" to "higher" forms of life, and it does not increase in complexity. For example, bacteria have simpler structures and a smaller amount of genetic material than humans do. This does not mean however, that bacteria are "less evolved" than humans are. Bacteria have evolved over many millions of years and are well adapted to their own environments.

After Darwin

Since Darwin's time, scientists have gathered a more complete fossil record, including microorganisms and chemical fossils. These fossils have supported and added more information to Darwin's theories. However, the age of the Earth is now held to be much older than Darwin thought. Researchers have also uncovered some of the preliminary mysteries of the mechanism of heredity as carried out through genetics and DNA, which were areas unknown to Darwin. Another growing subject is the study of comparative anatomy, which looks at how different organisms have similar body structures. Molecular biology studies of slowly changing genes reveal an evolutionary history that is consistent with fossil and anatomical records.

Lesson Summary

- Biochemistry is the study of the chemicals that make up life. Cell biology is the study of life at the level of the cell. Microbiology is the study of microscopic organisms. Genetics is the study of how organisms pass traits to their offspring. The study of how the human body works is called physiology. Zoology is the study of animals. The study of how organisms interact with their environment and each other is called ecology. Evolutionary biology is the study of how populations and species of animals change over time. Botany is the study of plants.
- The seven characteristics of life include: responsiveness to the environment; growth and change; ability to reproduce; have a metabolism and breathe; maintain homeostasis; being made of cells; passing traits onto offspring.
- Four unifying principles form the foundation of modern biology: cell theory, evolution, genetics and homeostasis. These four principles are important to each and every field of biology.
- Symbiosis can be used to describe various types of close relationships between organisms of different species, such as mutualism and commensalism, which are relationships in which neither organism is harmed. Sometimes the term symbiosis is used only for cases where both organisms benefit, but sometimes it is used more generally to describe all kinds of close relationships, even when one organism is killed by another. Symbiosis can also be used to describe relationships where one organism lives on or in another, called parasitism, or when one organism kills and eats another organism, called predation. Competition is as an interaction between organisms or species for the same resources in an environment.
- Analysis of the DNA of different organisms indicate that there is a similarity in the DNA genetic codes that help make proteins and other molecules in very different organisms. These genetic codes are used by all known forms of life on Earth, and are very similar. The theory of evolution suggests that the genetic code was established very early in the history of life and some studies suggest it was established soon after the formation of Earth.

Review Questions

1. Identify three of the seven characteristics of living things.
2. Identify the four unifying principles of modern biology.
3. List two different types of interactions that organisms can have with each other.
4. Outline the formation of modern evolutionary theory.
5. Give an example of how you are interdependent from another organism.
6. You find an object that looks like a dead, brown leaf, but it also looks like it might have eyes and legs–features that leaves do not usually have. How would you go about determining if this object was a living creature.
7. What is the basic unit of life?

8. What is homeostasis?
9. How have more recent scientific findings fit with evolutionary theory since Darwin's time?
10. Large animals are more evolved than single-celled organisms such as bacteria. Do you agree with this statement?

Further Reading / Supplemental Links

- http://en.wikibooks.org/wiki/Biology%2C_Answering_the_Big_Questions_of_Life/Introduction
- http://thinkexist.com/quotations/education/
- http://www.ucmp.berkeley.edu/help/timeform.html

Vocabulary

adaptation Refers to the process of becoming adjusted to an environment; may include structural, physiological, or behavioral traits that improve an organism's likelihood of survival and reproduction.

biochemistry The study of the chemicals that make up life.

biological interactions The interactions between different organisms in an environment.

biology The study of life.

biosphere Every place that life occurs, from the upper reaches of the atmosphere to the top few meters of soil, to the bottoms of the oceans.

botany The study of plants.

cell The smallest unit of structure and function of living organisms.

cell biology The study of life at the level of the cell.

community Composed of the relationships between groups of different species.

competition An interaction between organisms or species, for the same resources such as water, food, or hunting grounds in an environment.

ecology The study of how organisms interact with their environment and each other.

ecosystem Made up of the relationships among smaller groups of organisms with each other, and their environment.

evolution The process by which populations of organisms change over time by acquiring and passing on new traits from generation to generation.

evolutionary biology The study of how populations and species change over time.

genetics The study of how organisms pass traits to their offspring (heredity).

homeostasis The ability to keep an internal environment within a certain range, despite changes in the external environment.

immunology The study of an organism's resistance to disease.

metabolism The sum of the chemical reactions in a cell.

microbiology The study of microscopic organisms.

natural selection A process that causes heritable traits that are helpful for survival and reproduction to become more common, and harmful traits, or traits that are not helpful or advantageous for survival to become more rare in a population of organisms.

organism An individual living creature.

physiology The study of how the human body works.

symbiosis Various types of close relationships between organisms of different species; comes from a Greek word that means "living together."

zoology The study of animals.

Points to Consider

- All modern scientific disciplines support the theory of evolution. Consider what type of hypothesis could be made that might challenge evolutionary theory. Likewise, consider what type of hypothesis could challenge the cell theory.
- As you read through other chapters in this book, it might help to remember that studying biology does not just mean learning facts by memory or repetition. By studying biology you are developing a knowledge and understanding of the world around you. And, combined with your study of other subjects such as literature, social studies, art, music, mathematics, and physical sciences, you will develop a fuller, deeper understanding of what it is to be a human being who interacts with and lives an interdependent life with other organisms (including other humans!) in your environment.

"Intellectual growth should commence at birth and cease only at death." - **Albert Einstein**

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Chapter 2

Chemical Basis of Life

2.1 Lesson 2.1: Matter

Lesson Objectives

- Describe elements and compounds, and explain how mixtures differ from compounds.
- Define energy, and describe how energy can be changed from one form to another.
- Identify three states of matter, and explain how they differ.

Introduction

Living things are made of **matter.** In fact, matter is the "stuff" of which all things are made. Anything that occupies space and has mass is known as matter. Matter, in turn, consists of chemical substances.

Chemical Substances

A chemical substance is a material that has a definite chemical composition. It is also homogeneous, so the same chemical composition is found uniformly throughout the substance. A chemical substance may be an element or a chemical compound.

Elements

An **element** is a pure substance that cannot be broken down into different types of substances. Examples of elements include carbon, oxygen, hydrogen, and iron. Each element is made up of just one type of atom. An atom is the smallest particle of an element that still

characterizes the element. As shown in **Figure** 2.1, at the center of an atom is a nucleus. The nucleus contains positively charged particles called protons and electrically neutral particles called neutrons. Surrounding the nucleus is a much larger electron cloud consisting of negatively charged electrons. An atom is electrically neutral if it has the same number of protons as electrons. Each element has atoms with a characteristic number of protons. For example, all carbon atoms have six protons, and all oxygen atoms have eight protons.

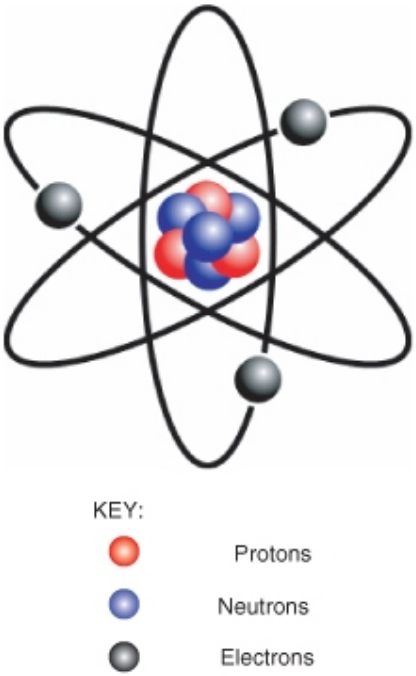


Figure 2.1: Model of an Atom. The protons and neutrons of this atom make up its nucleus. Electrons surround the nucleus. KEY: Red = protons, Blue = neutrons, Black = electrons.

There are almost 120 known elements (**Figure** 2.2). The majority of known elements are classified as metals. Metals are elements that are lustrous, or shiny. They are also good conductors of electricity and heat. Examples of metals include iron, gold, and copper. Fewer than 20 elements are classified as nonmetals. Nonmetals lack the properties of metals. Examples of nonmetals include oxygen, hydrogen, and sulfur. Certain other elements have properties of both metals and nonmetals. They are known as metalloids. Examples of metalloids include silicon and boron.

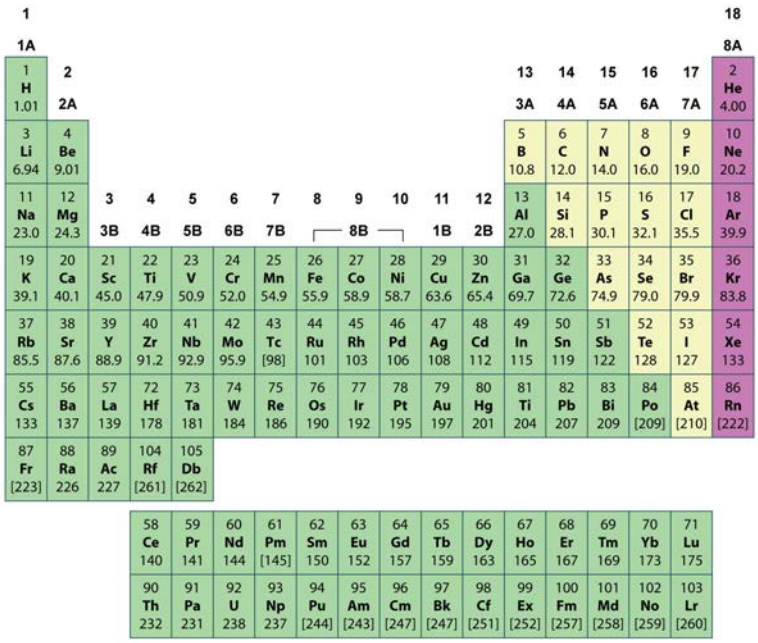


Figure 2.2: The Periodic Table.

Chemical Compounds

A **chemical compound** is a new substance that forms when atoms of two or more elements react with one another. A chemical reaction is a process that changes some chemical substances into other chemical substances. A compound that results from a chemical reaction always has a unique and fixed chemical composition. The substances in the compound can be separated from one another only by another chemical reaction. This is covered further in the *Chemical Reactions* lesson.

The atoms of a compound are held together by chemical bonds. Chemical bonds form when atoms share electrons. There are different types of chemical bonds, and they vary in how strongly they hold together the atoms of a compound. Two of the strongest types of bonds are covalent and ionic bonds. Covalent bonds form between atoms that have little if any difference in electronegativity. Electronegativity is the power of an atom to attract electrons toward itself. Ionic bonds, in contrast, form between atoms that are significantly different in electronegativity.

An example of a chemical compound is water. A water molecule forms when oxygen (O) and hydrogen (H) atoms react and are held together by covalent bonds. Like other compounds, water always has the same chemical composition: a 2:1 ratio of hydrogen atoms to oxygen atoms. This is expressed in the chemical formula H_2O. A model of a water molecule is shown in **Figure** 2.3.

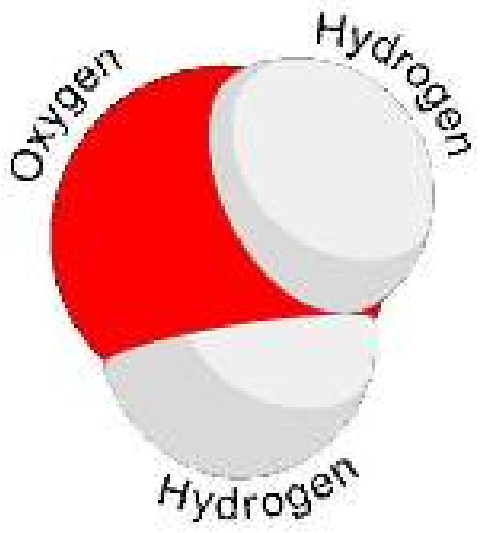


Figure 2.3: Model of a water molecule, showing the arrangement of hydrogen and oxygen atoms

Compounds that contain mainly the elements carbon and hydrogen are called **organic compounds**. This is because they are found mainly in living organisms. Most organic compounds are held together by covalent bonds. An example of an organic compound is glucose ($C_6H_{12}O_6$), which is shown in **Figure** 2.4. Glucose is a simple sugar that living cells use for energy. All other compounds are called inorganic compounds. Water is an example of an inorganic compound. You will read more about organic compounds in Lesson 2.2.

Mixtures vs. Compounds

Like a chemical compound, a **mixture** consists of more than one chemical substance. Unlike a compound, a mixture does not have a fixed chemical composition. The substances in a mixture can be combined in any proportions. A mixture also does not involve a chemical reaction. Therefore, the substances in a mixture are not changed into unique new substances, and they can be separated from each other without a chemical reaction.

The following examples illustrate these differences between mixtures and compounds. Both examples involve the same two elements: the metal iron (Fe) and the nonmetal sulfur (S).

- When iron filings and sulfur powder are mixed together in any ratio, they form a mixture. No chemical reaction occurs, and both elements retain their individual properties. A magnet can be used to mechanically separate the two elements by attracting the iron filings out of the mixture and leaving the sulfur behind.
- When iron and sulfur are mixed together in a certain ratio and heated, a chemical reaction occurs. This results in the formation of a unique new compound, called iron

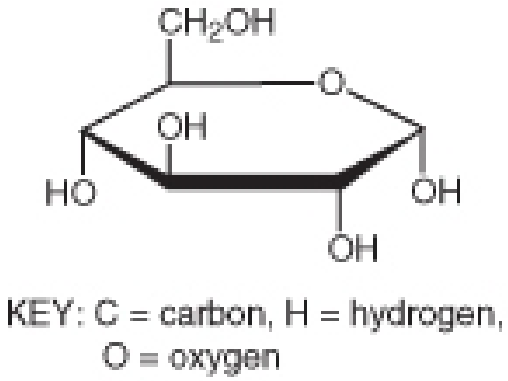


Figure 2.4: Glucose Molecule. This model represents a molecule of glucose, an organic compound composed of carbon, hydrogen, and oxygen. The chemical formula for glucose is CHO. This means that each molecule of glucose contains six carbon atoms, twelve hydrogen atoms, and six oxygen atoms. NOTE: Each unlabeled point where lines intersect represents another carbon atom. Some of these carbons and the oxygen atom are bonded to another hydrogen atom, not shown here.

sulfide (FeS). A magnet cannot be used to mechanically separate the iron from the iron sulfide because metallic iron does not exist in the compound. Instead, another chemical reaction is required to separate the iron and sulfur.

Matter and Energy

Energy is a property of matter that is defined as the ability to do work. The concept of energy is useful for explaining and predicting most natural phenomena, and it is foundational for an understanding of biology. All living organisms need energy to grow and reproduce. However, energy can never be created or destroyed. It is always conserved. This is called the law of conservation of energy. Therefore, organisms cannot create the energy they need. Instead, they must obtain energy from the environment. Organisms also cannot destroy or use up the energy they obtain. They can only change it from one form to another.

Forms of Energy

Energy can take several different forms. Common forms of energy include light, chemical, and heat energy. Other common forms are kinetic and potential energy.

How Organisms Change Energy

In organisms, energy is always changing from one form to another. For example, plants obtain light energy from sunlight and change it to chemical energy in food molecules. Chemical energy is energy stored in bonds between atoms within food molecules. When other organisms eat and digest the food, they break the chemical bonds and release the chemical energy. Organisms do not use energy very efficiently. About 90 percent of the energy they obtain from food is converted to heat energy that is given off to the environment.

Kinetic and Potential Energy

Energy also constantly changes back and forth between kinetic and potential energy. **Kinetic energy** is the energy of movement. For example, a ball falling through the air has kinetic energy because it is moving (**Figure** 2.5). **Potential energy** is the energy stored in an object due to its position. A bouncing ball at the top of a bounce, just before it starts to fall, has potential energy. For that instant, the ball is not moving, but it has the potential to move because gravity is pulling on it. Once the ball starts to fall, the potential energy changes to kinetic energy. When the ball hits the ground, it gains potential energy from the impact. The potential energy changes to kinetic energy when the ball bounces back up into the air. As the ball gains height, it regains potential energy because of gravity.

Figure 2.5: Energy in a bouncing ball is transformed from potential energy to kinetic energy and then back to potential energy. This cycle of energy changes keeps repeating as long as the ball continues to bounce. The ball rises less on each successive bounce because some energy is used to resist air molecules.

Like the ball, every time you move you have kinetic energy — whether you jump or run or just blink your eyes. Can you think of situations in which you have potential energy? Obvious examples might include when you are standing on a diving board or at the top of a ski slope or bungee jump. What gives you potential energy in all of these situations? The answer is gravity.

States of Matter

The amount of energy in molecules of matter determines the **state of matter**. Matter can exist in one of several different states, including a gas, liquid, or solid state. These different states of matter have different properties, which are illustrated in **Figure** 2.6.

- A **gas** is a state of matter in which atoms or molecules have enough energy to move freely. The molecules come into contact with one another only when they randomly collide. Forces between atoms or molecules are not strong enough to hold them together.
- A **liquid** is a state of matter in which atoms or molecules are constantly in contact but have enough energy to keep changing positions relative to one another. Forces between atoms or molecules are strong enough to keep the molecules together but not strong enough to prevent them from moving.
- A **solid** is a state of matter in which atoms or molecules do not have enough energy to move. They are constantly in contact and in fixed positions relative to one another.

Forces between atoms or molecules are strong enough to keep the molecules together and to prevent them from moving.

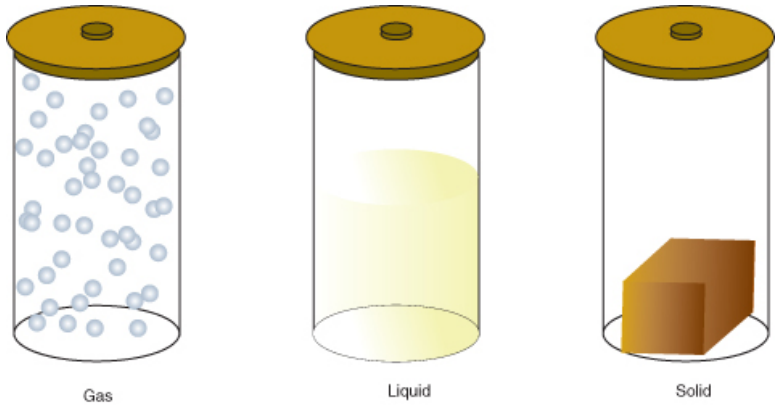


Figure 2.6: States of Matter.

All three containers contain a substance with the same mass, but the substances are in different states. In the left-hand container, the substance is a gas, which has spread to fill its container. It takes both the shape and volume of the container. In the middle container, the substance is a liquid, which has spread to take the shape of its container but not the volume. In the right-hand container, the substance is a solid, which takes neither the shape nor the volume of its container.

What Determines a Substance's State?

Which state a substance is in depends partly on temperature and air pressure. For example, at the air pressure found at sea level, water exists as a liquid at temperatures between 0° C and 100° C. Above 100° C, water exists as a gas (water vapor). Below 0° C, water exists as a solid (ice). Different substances have a different range of temperatures at which they exist in each state. For example, oxygen is gas above -183° C, but iron is a gas only above 2861° C. These differences explain why some substances are always solids at normal Earth temperatures, whereas others are always gases or liquids.

Changing States

Matter constantly goes through cycles that involve changing states. Water and all the elements important to organisms, including carbon and nitrogen, are constantly recycled on Earth (see *Principles of Ecology*). As matter moves through its cycles, it changes state repeatedly. For example, in the water cycle, water repeatedly changes from a gas to a liquid or solid and back to a gas again. How does this happen?

Adding energy to matter gives its atoms or molecules the ability to resist some of the forces holding them together. For example, heating ice to its melting point (0°C) gives its molecules enough energy to move. The ice melts and becomes liquid water. Similarly, heating liquid water to its boiling point (100°C) gives its molecules enough energy to pull apart from one another so they no longer have contact. The liquid water vaporizes and becomes water vapor.

Lesson Summary

- Matter consists of elements and compounds. A compound forms when elements combine in fixed proportions and undergo a chemical reaction. A mixture forms when substances combine in any proportions without a chemical reaction.
- Energy is a property of matter. It cannot be created or destroyed. Organisms obtain light energy from sunlight or chemical energy from food and change the energy into different forms, including heat energy.
- Matter can exist in one of several different states, including a gas, liquid, or solid state. States of matter differ in the amount of energy their molecules have. When matter recycles, it changes state by gaining or losing energy.

Review Questions

1. Define element, and give an example of an element.
2. State how a compound differs from an element, and give an example of a compound.
3. What is energy?
4. What are three common states of matter?
5. Describe two ways that energy changes form in the following sequence of events: A plant grows in the sun. $\rightarrow$ A rabbit eats the plant.
6. Describe a real-life situation in which the energy of an object or person changes back and forth between kinetic energy and potential energy. Identify each time energy changes form.
7. Compare and contrast mixtures and compounds.
8. Explain what happens to molecules of matter when matter changes state from a liquid to a gas.

Further Reading / Supplemental Links

- David Bodanis, *$E = mc^2$: A Biography of the World's Most Famous Question.* Walker and Co., 2005.
- John Emsley, *Nature's Building Blocks: An A-Z Guide to the Elements.* Oxford University Press, 2003.
- Nevin Katz, *Elements, Compounds, and Mixtures: Middle and High School (Mr. Birdley Teaches Science).* Incentive Publications, 2007.

- http://en.wikipedia.org

Vocabulary

chemical compound Unique substance with a fixed composition that forms when atoms of two or more elements react.

element Pure substance made up of just one type of atom.

energy Property of matter that is defined as the ability to do work.

gas State of matter in which atoms or molecules have enough energy to move freely.

kinetic energy Form of energy that an object has when it is moving.

liquid State of matter in which atoms or molecules are constantly in contact but have enough energy to keep changing positions relative to one another.

matter All the substances of which things are made.

mixture Combination of chemical substances that does not have a fixed composition and does not result from a chemical reaction.

organic compound Type of chemical compound that contains carbon and hydrogen and is found mainly in organisms.

potential energy Form of energy that is stored in an object due to its position.

solid State of matter in which atoms or molecules do not have enough energy to move.

state of matter Condition that matter is in, depending on how much energy its atoms or molecules have.

Points to Consider

Like all living things, you contain many organic compounds. For example, your brain is using the organic compound glucose as you read these words. Glucose provides brain cells with energy.

- What are some other organic compounds in your body?
- What roles do you think other organic compounds might play?
- Why are organic compounds able to carry out these roles?
- How do organic compounds differ from inorganic compounds?

2.2 Lesson 2.2: Organic Compounds

Lesson Objectives

- Explain why **carbon** is essential to life on Earth.
- Describe the structure and function of carbohydrates.
- Describe the structure and function of lipids.
- Describe the structure and function of proteins.
- Describe the structure and function of nucleic acids.

Introduction

Organic compounds are chemical substances that make up organisms and carry out life processes. All organic compounds contain the elements carbon and hydrogen. Because carbon is the major element in organic compounds, it is essential to all known life on Earth. Without carbon, life as we know it could not exist.

The Significance of Carbon

Why is carbon so important to organisms? The answer lies with carbon's unique properties. Carbon has an exceptional ability to bind with a wide variety of other elements. Carbon atoms can form multiple stable bonds with other small atoms, including hydrogen, oxygen, and nitrogen. Carbon atoms can also form stable bonds with other carbon atoms. In fact, a carbon atom may form single, double, or even triple bonds with other carbon atoms. This allows carbon atoms to form a tremendous variety of very large and complex molecules.

Nearly 10 million carbon-containing organic compounds are known. Types of carbon compounds in organisms include carbohydrates, lipids, proteins, and nucleic acids. The elements found in each type are listed in Table 1. Elements other than carbon and hydrogen usually occur within organic compounds in smaller groups of elements called **functional groups**. When organic compounds react with other compounds, generally just the functional groups are involved. Therefore, functional groups generally determine the nature and functions of organic compounds.

Table 2.1: **Organic Compounds**

Type of Compound	Elements It Contains	Examples
Carbohydrates	Carbon, hydrogen, oxygen	Glucose, Starch, Glycogen
Lipids	Carbon, hydrogen, oxygen	Cholesterol, Triglycerides (fats) Phospholipids

Table 2.1: (continued)

Type of Compound	Elements It Contains	Examples
Proteins	Carbon, hydrogen, oxygen, nitrogen, sulfur	Enzymes, Antibodies
Nucleic Acids	Carbon, hydrogen, oxygen, nitrogen, phosphorus	Deoxyribonucleic acid (DNA) Ribonucleic acid (RNA)

This table lists the four types of organic compounds, the elements they contain, and examples of each type of compound.

Carbohydrates

Carbohydrates are organic compounds that contain only carbon, hydrogen, and oxygen. They are the most common of the four major types of organic compounds. There are thousands of different carbohydrates, but they all consist of one or more smaller units called monosaccharides.

Monosaccharides and Disaccharides

The general formula for a **monosaccharide** is:

$(CH_2O)_n$,

where n can be any number greater than two. For example, if n is 6, then the formula can be written:

$C_6H_{12}O_6$.

This is the formula for the monosaccharide glucose. Another monosaccharide, fructose, has the same chemical formula as glucose, but the atoms are arranged differently. Molecules with the same chemical formula but with atoms in a different arrangement are called isomers. Compare the glucose and fructose molecules in **Figure** 2.7. Can you identify their differences? The only differences are the positions of some of the atoms. These differences affect the properties of the two monosaccharides.

If two monosaccharides bond together, they form a carbohydrate called a **disaccharide**. An example of a disaccharide is sucrose (table sugar), which consists of the monosaccharides glucose and fructose (**Figure** 2.7). Monosaccharides and disaccharides are also called **simple sugars**. They provide the major source of energy to living cells.

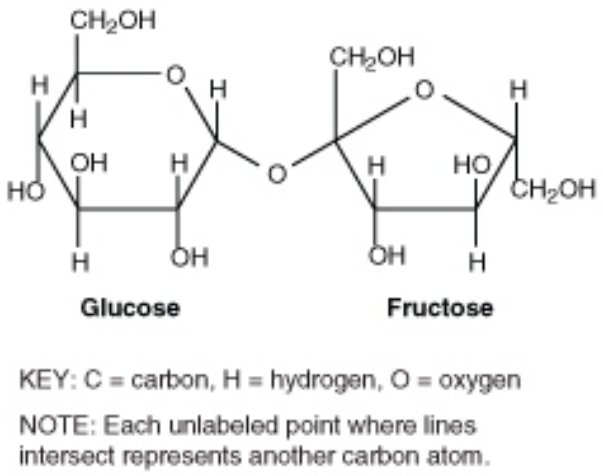


Figure 2.7: Sucrose Molecule. This sucrose molecule is a disaccharide. It is made up of two monosaccharides: glucose on the left and fructose on the right.

Polysaccharides

If more than two monosaccharides bond together, they form a carbohydrate called a **polysaccharide**. A polysaccharide may contain anywhere from a few monosaccharides to several thousand monosaccharides. Polysaccharides are also called **complex carbohydrates**. Their main functions are to store energy and form structural tissues. Examples of several polysaccharides and their roles are listed in Table 2.

Table 2.2: **Complex Carbohydrates**

Complex Carbohydrate	Function	Organism
Amylose	Stores energy	Plants
Glycogen	Stores energy	Animals
Cellulose	Forms cell walls	Plants
Chitin	Forms external skeleton	Some animals

These complex carbohydrates play important roles in living organisms.

Lipids

Lipids are organic compounds that contain mainly carbon, hydrogen, and oxygen. They include substances such as fats and oils. Lipid molecules consist of fatty acids, with or without additional molecules. **Fatty acids** are organic compounds that have the general formula $CH_3(CH_2)_nCOOH$, where n usually ranges from 2 to 28 and is always an even number.

Saturated and Unsaturated Fatty Acids

Fatty acids can be saturated or unsaturated. The term saturated refers to the placement

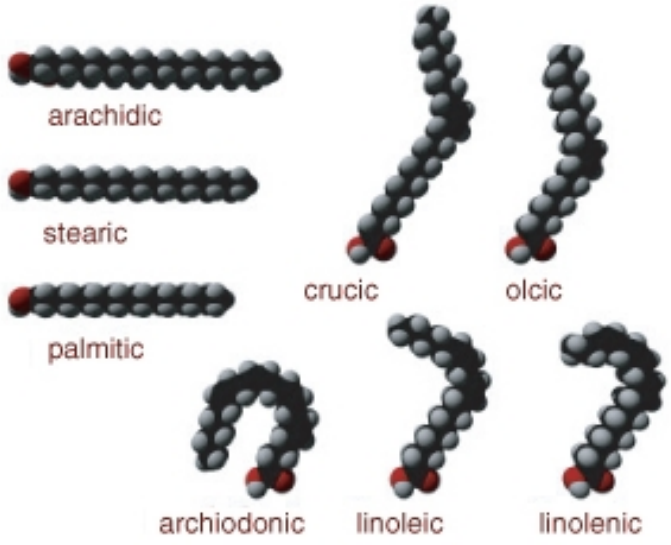


Figure 2.8: Saturated and Unsaturated Fatty Acids. Saturated fatty acids include arachidic, stearic, and palmitic fatty acids, shown on the left in this figure. Unsaturated fatty acids include all the other fatty acids in the figure. Notice how all the unsaturated fatty acids have bent chains, whereas the saturated fatty acids have straight chains.

gives unsaturated fatty acids different properties than saturated fatty acids. For example, unsaturated fatty acids are liquids at room temperature whereas saturated fatty acids are solids. Unsaturated fatty acids are found mainly in plants, especially in fatty tissues such as nuts and seeds.

Unsaturated fatty acids occur naturally in the bent shapes shown in **Figure** 2.8. However, unsaturated fatty acids can be artificially manufactured to have straight chains like saturated fatty acids. Called **trans fatty acids**, these synthetic lipids were commonly added to foods, until it was found that they increased the risk for certain health problems. Many food manufacturers no longer use trans fatty acids for this reason.

Types of Lipids

Lipids may consist of fatty acids alone or in combination with other compounds. Several types of lipids consist of fatty acids combined with a molecule of alcohol:

- **Triglycerides** are the main form of stored energy in animals. This type of lipid is commonly called fat. A triglyceride is shown in **Figure** 2.9.
- **Phospholipids** are a major component of the membranes surrounding the cells of all organisms.

- **Steroids** (or sterols) have several functions. The sterol **cholesterol** is an important part of cell membranes and plays other vital roles in the body. Other steroids are male and female sex hormones (see *Reproductive System and Human Development*).

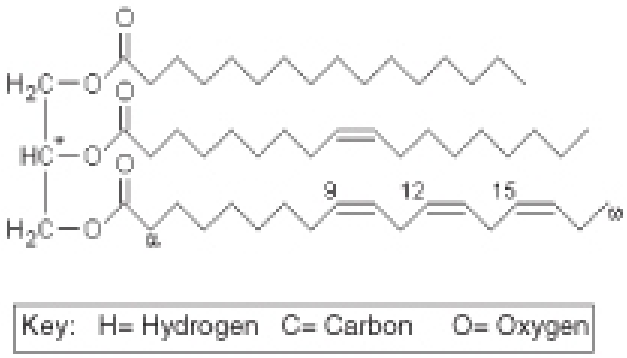


Figure 2.9: Triglyceride Molecule. The left part of this triglyceride molecule represents glycerol. Each of the three long chains on the right represents a different fatty acid. From top to bottom, the fatty acids are palmitic acid, oleic acid, and alpha-linolenic acid. The chemical formula for this triglyceride is CHO. KEY:H=hydrogen, C=carbon, O=oxygen

Lipids and Diet

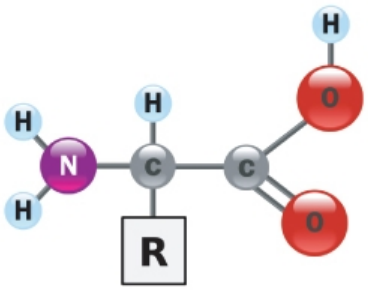
Humans need lipids for many vital functions, such as storing energy and forming cell membranes. Lipids can also supply cells with energy. In fact, a gram of lipids supplies more than twice as much energy as a gram of carbohydrates or proteins. Lipids are necessary in the diet for most of these functions. Although the human body can manufacture most of the lipids it needs, there are others, called **essential fatty acids**, that must be consumed in food. Essential fatty acids include omega-3 and omega-6 fatty acids. Both of these fatty acids are needed for important biological processes, not just for energy.

Although some lipids in the diet are essential, excess dietary lipids can be harmful. Because lipids are very high in energy, eating too many may lead to unhealthy weight gain. A high-fat diet may also increase lipid levels in the blood. This, in turn, can increase the risk for health problems such as cardiovascular disease (see Circulatory and Respiratory Systems). The dietary lipids of most concern are saturated fatty acids, trans fats, and cholesterol. For example, cholesterol is the lipid mainly responsible for narrowing arteries and causing the disease atherosclerosis.

Proteins

Proteins are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. Proteins are made of smaller units called **amino acids**. There are 20 different common amino acids needed to make proteins. All amino acids have the same basic structure, which is shown in **Figure** 2.10. Only the side chain (labeled R in the figure) differs from one amino acid to another. The variable side chain gives each amino acid unique properties. Proteins can differ from one another in the number and sequence (order) of amino acids. It is because of the side chains of the amino acids that proteins with different amino acid sequences have different shapes and different chemical properties.

Small proteins can contain just a few hundred amino acids. Yeast proteins average 466 amino acids. The largest known proteins are the titins, found in muscle, which are composed from almost 27,000 amino acids.



KEY: H = hydrogen , N = nitogen , C = carbon , R = variable side chain

Figure 2.10: General Structure of Amino Acids. This model shows the general structure of all amino acids. Only the side chain, R, varies from one amino acid to another. For example, in the amino acid glycine, the side chain is simply hydrogen (H). In glutamic acid, in contrast, the side chain is CHCHCOOH. Variable side chains give amino acids acids different chemical properties. The order of amino acids, together with the properties of the amino acids, determines the shape of the protein, and the shape of the protein determines the function of the protein. KEY: H = hydrogen, N = nitrogen, C = carbon, O = oxygen, R = variable side chain

Protein Structure

Amino acids can bond together to form short chains called **peptides** or longer chains called **polypeptides** (**Figure** 2.11). Polypeptides may have as few as 40 amino acids or as many as several thousand. A protein consists of one or more polypeptide chains. The sequence of amino acids in a protein's polypeptide chain(s) determines the overall structure and chemical properties of the protein. Primary protein structure is sequence of a chain of amino acids.

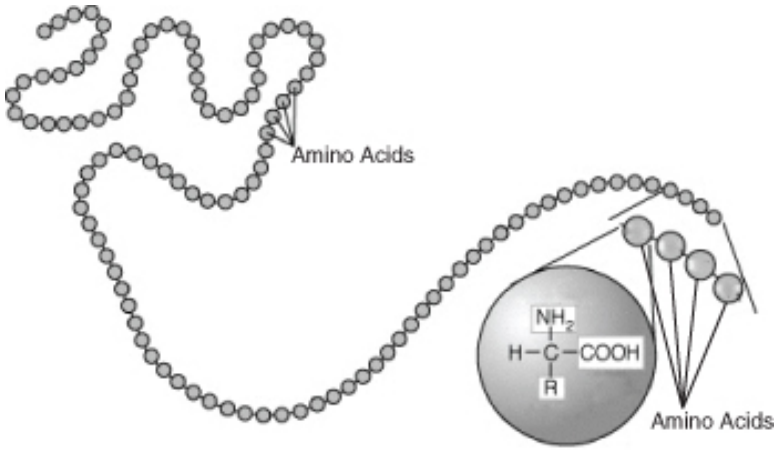


Figure 2.11: Polypeptide. This polypeptide is a chain made up of many linked amino acids.

The amino acid sequence is the primary structure of a protein. As explained in **Figure** 2.12, a protein may have up to four levels of structure, from primary to quaternary. The complex structure of a protein allows it to carry out its biological functions.

Functions of Proteins

Proteins are an essential part of all organisms. They play many roles in living things. Certain proteins provide a scaffolding that maintains the shape of cells. Proteins also make up the majority of muscle tissues. Many proteins are enzymes that speed up chemical reactions in cells (see the *Chemical Reactions* lesson). Other proteins are antibodies. They bond to foreign substances in the body and target them for destruction (see the Immune System and Disease chapter). Still other proteins help carry messages or materials in and out of cells or around the body. For example, the blood protein hemoglobin bonds with oxygen and carries it from the lungs to cells throughout the body.

One of the most important traits of proteins, allowing them to carry out these functions, is their ability to bond with other molecules. They can bond with other molecules very specifically and tightly. This ability, in turn, is due to the complex and highly specific structure of protein molecules.

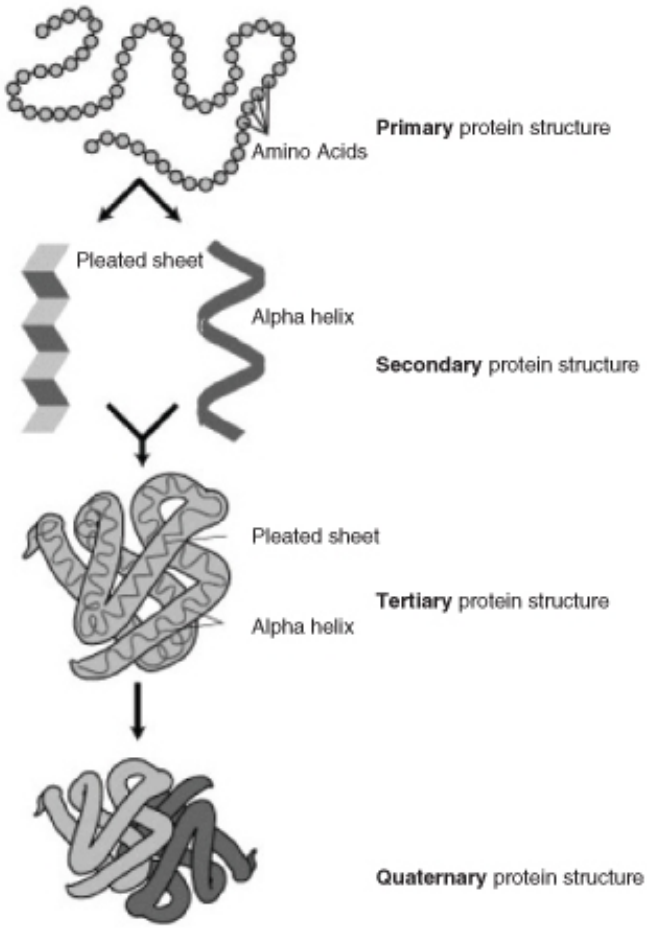


Figure 2.12: Protein Structure. Primary protein structure is the sequence of amino acids in a single polypeptide. Secondary protein structure refers to internal shapes, such as alpha helices and beta sheets, that a single polypeptide takes on due to bonds between atoms in different parts of the polypeptide. Tertiary protein structure is the overall three-dimensional shape of a protein consisting of one polypeptide. Quaternary protein structure is the shape of a protein consisting of two or more polypeptides. For a brief animation of protein structure, see .

Proteins and Diet

Proteins in the diet are necessary for life. Dietary proteins are broken down into their component amino acids when food is digested. Cells can then use the components to build new proteins. Humans are able to synthesize all but eight of the twenty common amino acids. These eight amino acids, called **essential amino acids**, must be consumed in foods. Like dietary carbohydrates and lipids, dietary proteins can also be broken down to provide cells with energy.

Nucleic Acids

Nucleic acids are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made of smaller units called **nucleotides**. Nucleic acids are named for the nucleus of the cell, where some of them are found. Nucleic acids are found not only in all living cells but also in viruses. Types of nucleic acids include **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**.

Structure of Nucleic Acids

A nucleic acid consists of one or two chains of nucleotides held together by chemical bonds. Each individual nucleotide unit consists of three parts:

- a base (containing nitrogen)
- a sugar (ribose in RNA, deoxyribose in DNA)
- a phosphate group (containing phosphorus)

The sugar of one nucleotide binds to the phosphate group of the next nucleotide. Alternating sugars and phosphate groups form the backbone of a nucleotide chain, as shown in **Figure** 2.13. The bases, which are bound to the sugars, stick out at right angles from the backbone of the chain.

RNA consists of a single chain of nucleotides, and DNA consists of two chains of nucleotides. Bonds form between the bases on the two chains of DNA and hold the chains together (**Figure** 2.13). There are four different types of bases in a nucleic acid molecule: cytosine, adenine, guanine, and either thymine (in DNA) or uracil (in RNA). Each type of base bonds with just one other type of base. Cytosine and guanine always bond together, and adenine and thymine (or uracil) always bond with one another. The pairs of bases that bond together are called **complementary bases**.

The binding of complementary bases allows DNA molecules to take their well-known shape, called a **double helix**. **Figure** 2.14 shows how two chains of nucleotides form a DNA double helix. A simplified double helix is illustrated in **Figure** 2.15. It shows more clearly

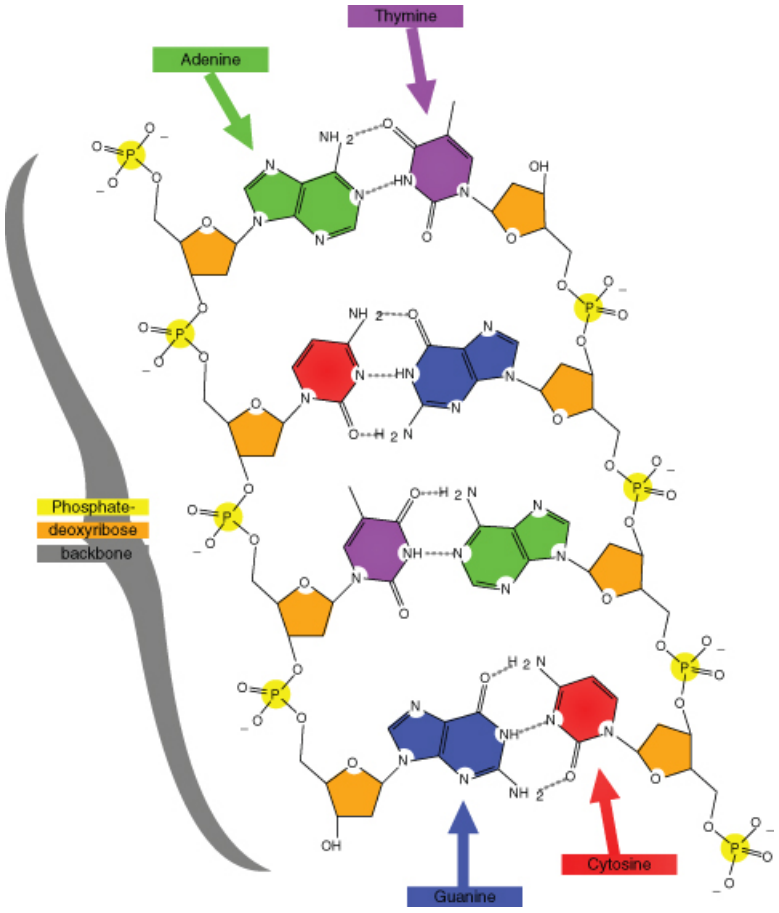


Figure 2.13: Part of a Nucleic Acid. This small section of a nucleic acid shows how phosphate groups (yellow) and sugars (orange) alternate to form the backbone of a nucleotide chain. The bases that jut out to the side from the backbone are adenine (green), thymine (purple), cytosine (pink), and guanine (blue). Bonds between complementary bases, such as between adenine and thymine, hold the two chains of nucleotides together. These bonds, called hydrogen bonds, are described in Lesson 2.4.

how the two chains are intertwined. The double helix shape forms naturally and is very strong. Being intertwined, the two chains are difficult to break apart. This is important given the fundamental role of DNA in all living organisms.

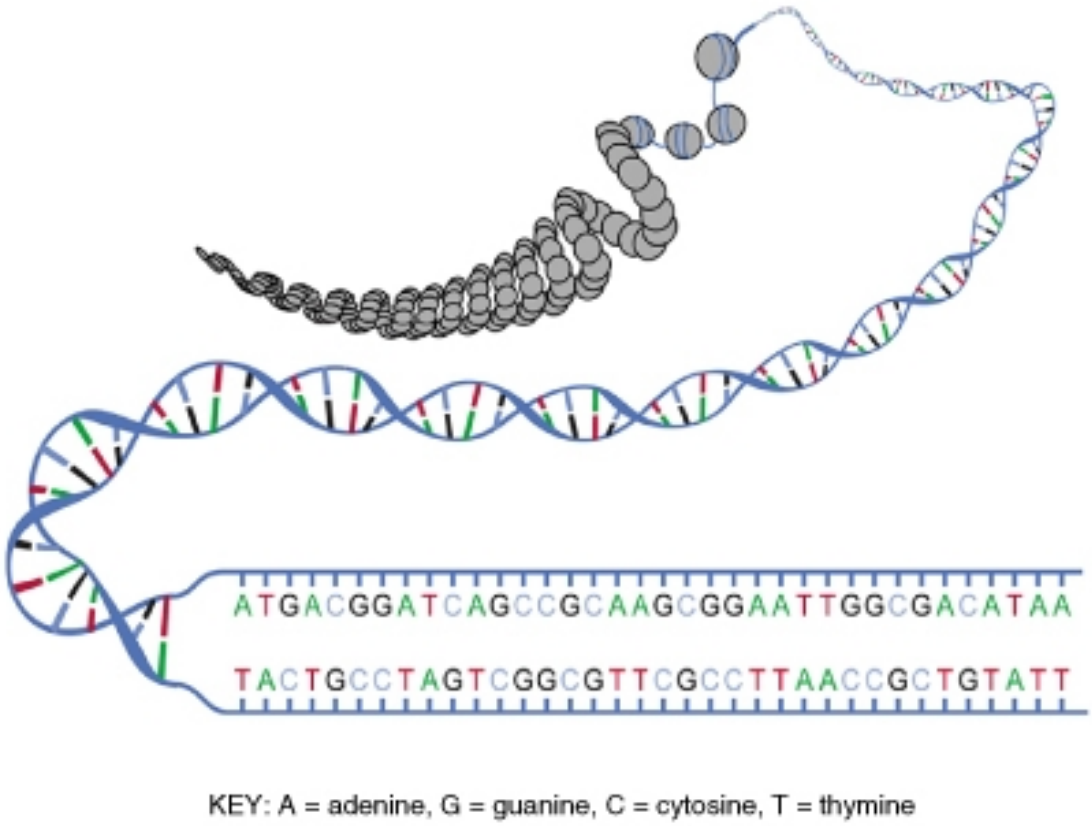


Figure 2.14: Double-Stranded Nucleic Acid. In this double-stranded nucleic acid, complementary bases (A and T, C and G) form bonds that hold the two nucleotide chains together in the shape of a double helix. Notice that A always bonds with T and C always bonds with G. These bonds help maintain the double helix shape of the molecule.

Role of Nucleic Acids

The order of bases in nucleic acids is highly significant. The bases are like the letters of a four-letter alphabet. These "letters" can be combined to form "words." Groups of three bases form words of the genetic code. Each code word stands for a different amino acid. A series of many code words spells out the sequence of amino acids in a protein (**Figure** 2.16). In short, nucleic acids contain the information needed for cells to make proteins. This

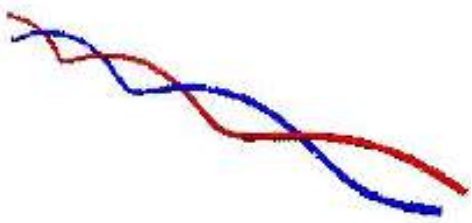


Figure 2.15: Simple Model of DNA. In this simple model of DNA, each line represents a nucleotide chain. The double helix shape forms when the two chains wrap around the same axis.

information is passed from a body cell to its daughter cells when the cell divides. It is also passed from parents to their offspring when organisms reproduce.

How RNA codes for Proteins

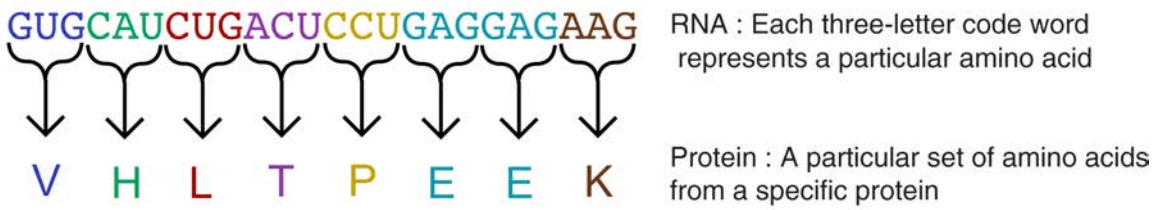


Figure 2.16: The letters G, U, C, and A stand for the bases in RNA. Each group of three bases makes up a code word, and each code word represents one amino acid (represented here by a single letter, such as V, H, or L). A string of code words specifies the sequence of amino acids in a protein.

DNA and RNA have different functions relating to the genetic code and proteins. Like a set of blueprints, DNA contains the genetic instructions for the correct sequence of amino acids in proteins. RNA uses the information in DNA to assemble the amino acids and make the proteins. You will read more about the genetic code and the role of nucleic acids in protein synthesis in Chapter 8.

Lesson Summary

- Carbon's exceptional ability to form bonds with other elements and with itself allows it to form a huge number of large, complex molecules called organic molecules. These molecules make up organisms and carry out life processes.
- Carbohydrates are organic molecules that consist of carbon, hydrogen, and oxygen. They are made up of repeating units called saccharides. They provide cells with energy, store energy, and form structural tissues.
- Lipids are organic compounds that consist of carbon, hydrogen, and oxygen. They are made up of fatty acids and other compounds. They provide cells with energy, store energy, and help form cell membranes.
- Proteins are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. They are made up of repeating units called amino acids. They provide cells with energy, form tissues, speed up chemical reactions throughout the body, and perform many other cellular functions.
- Nucleic acids are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made up of repeating units called nucleotides. They contain genetic instructions for proteins, help synthesize proteins, and pass genetic instructions on to daughter cells and offspring.

Review Questions

1. State the function of monosaccharides, such as glucose and fructose.
2. Why do molecules of saturated and unsaturated fatty acids have different shapes?
3. What determines the primary structure of a protein?
4. Identify the three parts of a nucleotide.
5. What type of organic compound is represented by the formula $CH_3(CH_2)_4COOH$? How do you know?
6. Bases in nucleic acids are represented by the letters A, G, C, and T (or U). How are the bases in nucleic acids like the letters of an alphabet.
7. Why is carbon essential to all known life on Earth?
8. Compare and contrast simple sugars and complex carbohydrates.
9. State two functions of proteins, and explain how the functions depend on the ability of proteins to bind other molecules to them.

Further Reading / Supplemental Links

- B.G. Davis and A.J. Fairbanks, *Carbohydrate Chemistry.* Oxford University Press, 2002.
- Michael I. Gurr, John L. Harwood, and Keith N. Frayn, *Lipid Biochemistry: An Introduction.* Wiley, 2005.

- James D. Watson, *The Double Helix: A Personal Account of the Discovery of DNA*. Touchstone, 2001.
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- http://en.wikipedia.org

Vocabulary

amino acid Small organic molecule that is a building block of proteins.

carbohydrate Type of organic compound that consists of one or more smaller units called monosaccharides.

cholesterol Type of steroid that is an important part of cell membranes and plays other vital roles.

complementary bases Nucleic acid bases that form bonds with each other and help hold together two nucleotide chains.

complex carbohydrate Another term for a polysaccharide.

deoxyribonucleic acid (DNA) Double-stranded nucleic acid that contains the genetic instructions for proteins.

disaccharide Small carbohydrate, such as sucrose, that consists of two monosaccharides.

double helix Normal shape of a DNA molecule in which two chains of nucleotides are intertwined.

essential amino acids Amino acids that the human body needs but cannot make and must consume in food.

essential fatty acids Fatty acids that the human body needs but cannot make and must consume in food.

fatty acid Organic compound found in lipids that has the general formula $CH_3(CH_2)_nCOOH$.

functional group Small group of elements within an organic compound that determines the nature and function of the organic compound.

lipid Type of organic compound that consists of one or more fatty acids with or without additional molecules.

monosaccharide Small carbohydrate, such as glucose, with the general formula $(CH_2O)_n$.

nucleic acid Type of organic compound that consists of smaller units called nucleotides.

nucleotide Small organic molecule that is a building block of nucleic acids.

peptide Short chain of amino acids.

phospholipid Type of lipid that is a major component of cell membranes.

polypeptide Long chain of amino acids.

polysaccharide Large carbohydrate that consists of more than two monosaccharides.

protein Type of organic compound that consists of smaller units called amino acids.

ribonucleic acid (RNA) Single-stranded nucleic acid that uses information contained in DNA to assemble amino acids and make proteins.

saturated fatty acid Type of fatty acid in which all the carbon atoms are bonded to as many hydrogen atoms as possible.

simple sugar Another term for a monosaccharide or disaccharide.

steroid Type of lipid that has several functions, such as forming cell membranes and acting as sex hormones.

trans fatty acid Artificial, unsaturated fatty acid that has properties similar to saturated fatty acids.

triglyceride Type of lipid that is the main form of stored energy in animals.

unsaturated fatty acid Type of fatty acid in which some carbon atoms are not bonded to as many hydrogen atoms as possible.

Points to Consider

Organisms are made up of thousands of very large, complex molecules called organic molecules. These molecules consist of repeating units of smaller molecules, such as amino acids or nucleotides.

- How do organic molecules form?
- How do smaller molecules join together to form larger molecules?
- What chemical processes are involved?

2.3 Lesson 2.3: Chemical Reactions

Lesson Objectives

- Describe what happens in a chemical reaction, and identify types of chemical reactions.
- Explain the role of energy in chemical reactions, and define activation energy.
- State factors that affect the rate of chemical reactions.
- Explain the importance of enzymes in organisms, and describe how enzymes work.

Introduction

A chemical compound may be very different from the substances that combine to form it. For example, the element chlorine (Cl) is a poisonous gas, but when it combines with sodium (Na) to form sodium chloride (NaCl), it is no longer toxic. You may even eat it on your food. Sodium chloride is just table salt. What process changes a toxic chemical like chlorine into a much different substance like table salt?

What are Chemical Reactions?

A **chemical reaction** is a process that changes some chemical substances into other chemical substances. The substances that start a chemical reaction are called **reactants**. The substances that form as a result of a chemical reaction are called **products**. During the reaction, the reactants are used up to create the products. For example, when methane burns in oxygen, it releases carbon dioxide and water. In this reaction, the reactants are methane (CH_4) and oxygen (O_2), and the products are carbon dioxide (CO_2) and water (H_2O).

Chemical Equations

A chemical reaction can be represented by a chemical equation. Using the same example, the burning of methane gas can be represented by the equation:

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$.

The arrow in a chemical equation separates the reactants from the products and shows the direction in which the reaction occurs. If the reaction could also occur in the opposite direction, then two arrows, one pointing in each direction, would be used. On each side of the arrow, a mixture of chemicals is indicated by the chemical symbols joined by a plus sign (+). The numbers preceding some of the chemical symbols (such as 2 O_2) indicate how many molecules of the chemicals are involved in the reaction. (If there is no number in front of a chemical symbol, it means that just one molecule is involved.)

In a chemical reaction, the quantity of each element does not change. There is the same amount of each element at the end of the reaction as there was at the beginning. This is reflected in the chemical equation for the reaction. The equation should be balanced. In a balanced equation, the same number of atoms of a given element appear on each side of the arrow. For example, in the equation above, there are four hydrogen atoms on each side of the arrow.

Types of Chemical Reactions

In general, a chemical reaction involves the breaking and forming of chemical bonds. In the methane reaction above, bonds are broken in methane and oxygen, and bonds are formed in carbon dioxide and water. A reaction like this, in which a compound or element burns in oxygen, is called a **combustion reaction**. This is just one of many possible types of chemical reactions. Other types of chemical reactions include synthesis, decomposition, and substitution reactions.

- A **synthesis reaction** occurs when two or more chemical elements or compounds unite to form a more complex product. For example, nitrogen (N_2) and hydrogen (H_2) unite to form ammonia (NH_3):

$N_2 + 3\ H_2 \rightarrow 2\ NH_3$.

- A **decomposition reaction** occurs when a compound is broken down into smaller compounds or elements. For example, water (H_2O) breaks down into hydrogen (H_2) and oxygen (O_2):

$2\ H_2O \rightarrow 2\ H_2 + O_2$.

- A **substitution reaction** occurs when one element replaces another element in a compound. For example, sodium (Na^+) replaces hydrogen (H) in hydrochloric acid (HCl), producing sodium chloride (NaCl) and hydrogen gas (H_2):

$2\ Na^+ + 2\ HCl \rightarrow 2\ NaCl + H_2$.

Chemical Reactions and Energy

Some chemical reactions consume energy, whereas other chemical reactions release energy. Each of the energy changes that occur during a reaction are graphed in **Figure** 2.17. In the reaction on the left, energy is released. In the reaction on the right, energy is consumed.

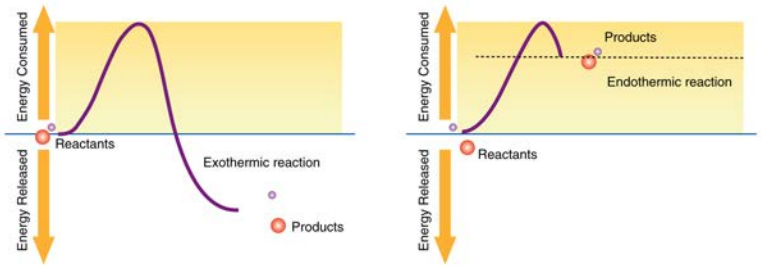

Figure 2.17: The reaction on the left releases energy. The reaction on the right consumes energy.

Exothermic Reactions

Chemical reactions that release energy are called **exothermic reactions**. An example is the combustion of methane described at the beginning of this lesson. In organisms, exothermic reactions are called **catabolic reactions**. Catabolic reactions break down molecules into smaller units. An example is the breakdown of glucose molecules for energy. Exothermic reactions can be represented by the general chemical equation:

Reactants $\rightarrow$ Products + Heat.

Endothermic Reactions

Chemical reactions that consume energy are called **endothermic reactions**. An example is the synthesis of ammonia, described above. In organisms, endothermic reactions are called **anabolic reactions**. Anabolic reactions construct molecules from smaller units. An example is the synthesis of proteins from amino acids. Endothermic reactions can be represented by the general chemical equation:

Reactants + Heat $\rightarrow$ Products.

Activation Energy

Regardless of whether reactions are exothermic or endothermic, they all need energy to get started. This energy is called **activation energy**. Activation energy is like the push you

need to start moving down a slide. The push gives you enough energy to start moving. Once you start, you keep moving without being pushed again. The concept of activation energy is illustrated in **Figure** 2.18.

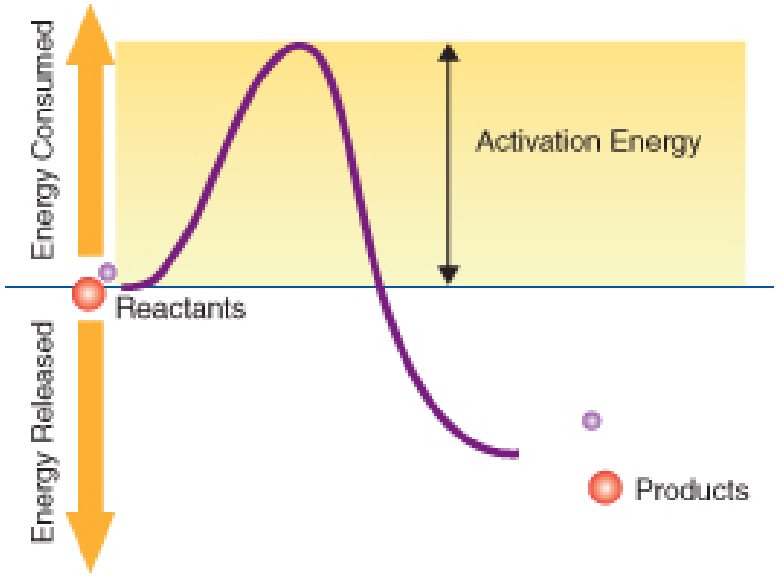

Figure 2.18: To start this reaction, a certain amount of energy is required, called the activation energy. How much activation energy is required depends on the nature of the reaction and the conditions under which the reaction takes place.

Why do reactions need energy to get started? In order for reactions to occur, three things must happen, and they all require energy:

- Reactant molecules must collide. To collide, they must move, so they need kinetic energy.
- Unless reactant molecules are positioned correctly, intermolecular forces may push them apart. To overcome these forces and move together requires more energy.
- If reactant molecules collide and move together, there must be enough energy left for them to react.

Rates of Chemical Reactions

The rates at which chemical reactions take place in organisms are very important. Chemical reactions in organisms are involved in processes ranging from the contraction of muscles to the digestion of food. For example, when you wave goodbye, it requires repeated contractions

of muscles in your arm over a period of a couple of seconds. A huge number of reactions must take place in that time, so each reaction cannot take longer than a few milliseconds. If the reactions took much longer, you might not finish waving until sometime next year.

Factors that help reactant molecules collide and react speed up chemical reactions. These factors include the concentration of reactants and the temperature at which the reactions occur.

- Reactions are usually faster at higher concentrations of reactants. The more reactant molecules there are in a given space, the more likely they are to collide and react.

- Reactions are usually faster at higher temperatures. Reactant molecules at higher temperatures have more energy to move, collide, and react.

Enzymes and Biochemical Reactions

Most chemical reactions within organisms would be impossible under the conditions in cells. For example, the body temperature of most organisms is too low for reactions to occur quickly enough to carry out life processes. Reactants may also be present in such low concentrations that it is unlikely they will meet and collide. Therefore, the rate of most biochemical reactions must be increased by a catalyst. A catalyst is a chemical that speeds up chemical reactions. In organisms, catalysts are called **enzymes**.

Like other catalysts, enzymes are not reactants in the reactions they control. They help the reactants interact but are not used up in the reactions. Instead, they may be used over and over again. Unlike other catalysts, enzymes are usually highly specific for particular chemical reactions. They generally catalyze only one or a few types of reactions.

Enzymes are extremely efficient in speeding up reactions. They can catalyze up to several million reactions per second. As a result, the difference in rates of biochemical reactions with and without enzymes may be enormous. A typical biochemical reaction might take hours or even days to occur under normal cellular conditions without an enzyme but less than a second with the enzyme. For an animation of a reaction in the presence or absence of an enzyme, see http://www.stolaf.edu/people/giannini/flashanimat/enzymes/prox-orien.swf.

How Enzymes Work

How do enzymes speed up biochemical reactions so dramatically? Like all catalysts, enzymes work by lowering the activation energy of chemical reactions. This is illustrated in **Figure** 2.19. The biochemical reaction shown in the figure requires about three times as much activation energy without the enzyme as it does with the enzyme. An animation of this process can be viewed at http://www.stolaf.edu/people/giannini/flashanimat/enzymes/transition%20state.swf.

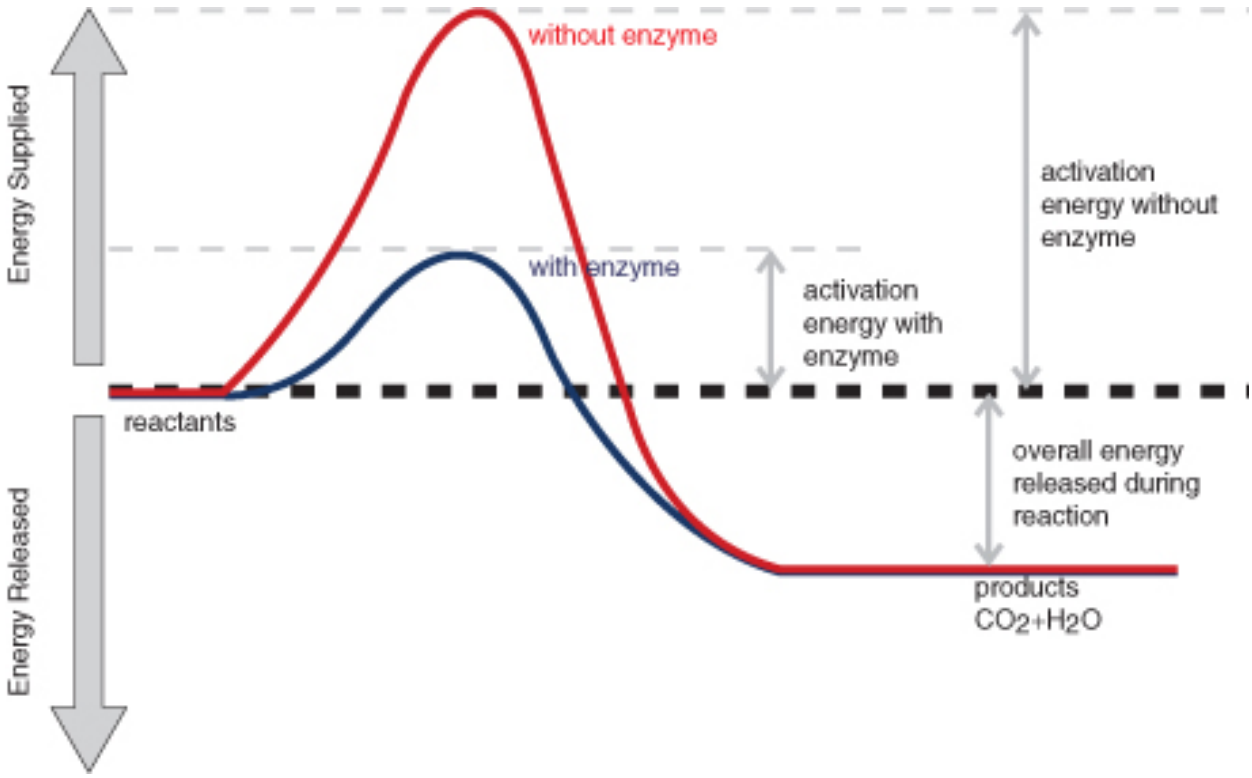

Figure 2.19: The reaction represented by this graph is a combustion reaction involving the reactants glucose (CHO) and oxygen (O). The products of the reaction are carbon dioxide (CO) and water (HO). Energy is also released during the reaction. The enzyme speeds up the reaction by lowering the activation energy needed for the reaction to start. Compare the activation energy with and without the enzyme.

Enzymes generally lower activation energy by reducing the energy needed for reactants to come together and react. For example:

- Enzymes bring reactants together so they don't have to expend energy moving about until they collide at random. Enzymes bind both reactant molecules (called substrate), tightly and specifically, at a site on the enzyme molecule called the active site (**Figure** 2.20).

- By binding reactants at the active site, enzymes also position reactants correctly, so they do not have to overcome intermolecular forces that would otherwise push them apart. This allows the molecules to interact with less energy.

- Enzymes may also allow reactions to occur by different pathways that have lower activation energy.

The activities of enzymes also depend on the temperature, ionic conditions, and the pH of the surroundings.

Some enzymes work best at acidic pHs, while others work best in neutral environments.

- Digestive enzymes secreted in the acidic environment (low pH) of the stomach help break down proteins into smaller molecules. The main digestive enzyme in the stomach is pepsin, which works best at a pH of about 1.5 (see the *Digestive and Excretory Systems* chapter). These enzymes would not work optimally at other pHs. Trypsin is another enzyme in the digestive system which break protein chains in the food into smaller parts. Trypsin works in the small intestine, which is not an acidic environment. Trypsin's optimum pH is about 8.

- Biochemical reactions are optimal at physiological temperatures. For example, most biochemical reactions work best at the normal body temperature of 98.6 $^{\circ}$F. Many enzymes lose function at lower and higher temperatures. At higher temperatures, an enzyme's shape deteriorates and only when the temperature comes back to normal does the enzyme regain its shape and normal activity.

Importance of Enzymes

Enzymes are involved in most of the chemical reactions that take place in organisms. About 4,000 such reactions are known to be catalyzed by enzymes, but the number may be even higher. Needed for reactions that regulate cells, enzymes allow movement, transport materials around the body, and move substances in and out of cells.

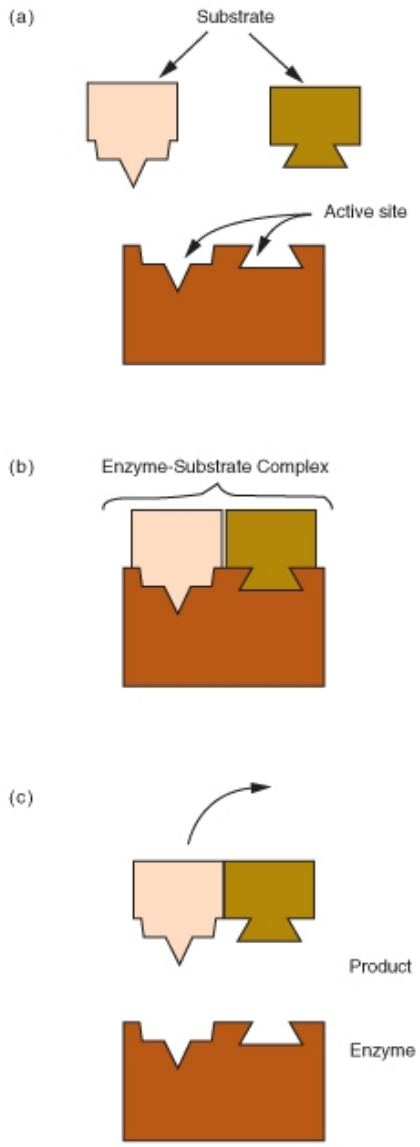

Figure 2.20: This enzyme molecule binds reactant molecules—called substrate—at its active site, forming an enzyme-substrate complex. This brings the reactants together and positions them correctly so the reaction can occur. After the reaction, the products are released from the enzyme's active site. This frees up the enzyme so it can catalyze additional reactions.

In animals, another important function of enzymes is to help digest food. Digestive enzymes speed up reactions that break down large molecules of carbohydrates, proteins, and fats into smaller molecules the body can use (*See* Chapter: Digestive and Excretory Systems). Without digestive enzymes, animals would not be able to break down food molecules quickly enough to provide the energy and nutrients they need to survive.

Lesson Summary

- A chemical reaction is a process that changes some chemical substances into others. It involves breaking and forming chemical bonds. Types of chemical reactions include synthesis reactions and decomposition reactions.
- Some chemical reactions are exothermic, which means they release energy. Other chemical reactions are endothermic, which means they consume energy. All chemical reactions require activation energy, which is the energy needed to get a reaction started.
- Rates of chemical reactions depend on factors such as the concentration of reactants and the temperature at which reactions occur. Both factors affect the ability of reactant molecules to react.
- Enzymes are needed to speed up chemical reactions in organisms. They work by lowering the activation energy of reactions.

Review Questions

1. Identify the roles of reactants and products in a chemical reaction.
2. What is the general chemical equation for an endothermic reaction?
3. State two factors, other than enzymes, that speed up chemical reactions.
4. How do enzymes work to speed up chemical reactions?
5. What is wrong with the chemical equation below? How could you fix it? $CH_4 + O_2 \rightarrow CO_2 + 2\ H_2O$
6. What type of reaction is represented by the following chemical equation? Explain your answer. $2\ Na + 2\ HCL \rightarrow 2\ NaCl + H_2$
7. Why do all chemical reactions require activation energy?
8. Explain why organisms need enzymes to survive.

Further Reading / Supplemental Links

- Peter Atkins and Julio De Paula, *Physical Chemistry for the Life Sciences*. Oxford University Press, 2006.
- Rita Elkins, *Digestive Enzymes*. Woodland Publishing, 2007.
- James Keeler and Peter Wothers, *Why Chemical Reactions Happen*. Oxford University Press, 2003.
- George W. Roberts, *Chemical Reactions and Chemical Reactors*. Wiley, 2008.

- http://en.wikipedia.org

Summary Animations

- http://www.stolaf.edu/people/giannini/flashanimat

Vocabulary

activation energy Energy needed for a chemical reaction to get started.

anabolic reaction Endothermic reaction that occurs in organisms.

catabolic reaction Exothermic reaction that occurs in organisms.

chemical reaction Process that changes some chemical substances into other chemical substances.

combustion reaction Type of chemical reaction in which a compound or element burns in oxygen.

decomposition reaction Type of chemical reaction in which a compound is broken down into smaller compounds or elements.

endothermic reaction Any chemical reaction that consumes energy.

enzyme Chemical that speeds up chemical reactions in organisms.

exothermic reaction Any chemical reaction that releases energy.

product Substance that forms as a result of a chemical reaction.

reactant Substance involved in a chemical reaction that is present at the beginning of the reaction.

substitution reaction Type of chemical reaction in which one element replaces another element in a compound.

synthesis reaction Type of chemical reaction in which elements or compounds unite to form a more complex product.

Points to Consider

Most chemical reactions in organisms take place in an environment that is mostly water.

- What do you know about water?
- Are you aware that water has unique properties?
- Do you know how water behaves differently from most other substances on Earth?
- Do you know why water is necessary for life?

2.4 Lesson 2.4: Water

Lesson Objectives

- Describe the distribution of Earth's water, and outline the water cycle.
- Identify the chemical structure of water, and explain how it relates to water's unique properties.
- Define solution, and describe water's role as a solvent.
- State how water is used to define acids and bases, and identify the pH ranges of acids and bases.
- Explain why water is essential for life processes.

Introduction

Water, like carbon, has a special role in biology because of its importance to organisms. Water is essential to all known forms of life. Water, H_2O, such a simple molecule, yet it is this simplicity that gives water its unique properties and explains why water is so vital for life.

Water, Water Everywhere

Water is a common chemical substance on Earth. The term water generally refers to its liquid state. Water is a liquid over a wide range of standard temperatures and pressures. However, water can also occur as a solid (ice) or gas (water vapor).

Where Is All the Water?

Of all the water on Earth, about two percent is stored underground in spaces between rocks. A fraction of a percent exists in the air as water vapor, clouds, or precipitation. Another fraction of a percent occurs in the bodies of plants and animals. So where is most of Earth's water? It's on the surface of the planet. In fact, water covers about 70 percent of Earth's surface. Of water on Earth's surface, 97 percent is salt water, mainly in the ocean. Only 3 percent is freshwater. Most of the freshwater is frozen in glaciers and polar ice caps. The remaining freshwater occurs in rivers, lakes, and other freshwater features.

Although clean freshwater is essential to human life, in many parts of the world it is in short supply. The amount of freshwater is not the issue. There is plenty of freshwater to go around, because water constantly recycles on Earth. However, freshwater is not necessarily located where it is needed, and clean freshwater is not always available.

How Water Recycles

Like other matter on Earth, water is continuously recycled. Individual water molecules are always going through the water cycle (see the *Principles of Ecology* chapter). In fact, water molecules on Earth have been moving through the water cycle for billions of years. In this cycle, water evaporates from Earth's surface (or escapes from the surface in other ways), forms clouds, and falls back to the surface as precipitation. This cycle keeps repeating. Several processes change water from one state to another during the water cycle. They include:

- **Evaporation**—Liquid water on Earth's surface changes into water vapor in the atmosphere.
- **Sublimation**—Snow or ice on Earth's surface changes directly into water vapor in the atmosphere.
- **Transpiration**—Plants give off liquid water, most of which evaporates into the atmosphere.
- **Condensation**—Water vapor in the atmosphere changes to liquid water droplets, forming clouds or fog.
- **Precipitation**—Water droplets in clouds are pulled to Earth's surface by gravity, forming rain, snow, or other type of falling moisture.

Chemical Structure and Properties of Water

You are probably already familiar with many of water's properties. For example, you no doubt know that water is tasteless, odorless, and transparent. In small quantities, it is also colorless. However, when a large amount of water is observed, as in a lake or the ocean, it

is actually light blue in color. These and other properties of water depend on its chemical structure.

The transparency of water is important for organisms that live in water. Because water is transparent, sunlight can pass through it. Sunlight is needed by water plants and other water organisms for photosynthesis (see *Biomes, Ecosystems, and Communities* chapter).

Chemical Structure of Water

Each molecule of water consists of one atom of oxygen and two atoms of hydrogen, so it has the chemical formula H_2O. The arrangement of atoms in a water molecule, shown in **Figure 2.21**, explains many of water's chemical properties. In each water molecule, the nucleus of the oxygen atom (with 8 positively charged protons) attracts electrons much more strongly than do the hydrogen nuclei (with only one positively charged proton). This results in a negative electrical charge near the oxygen atom (due to the "pull" of the negatively charged electrons toward the oxygen nucleus) and a positive electrical charge near the hydrogen atoms. A difference in electrical charge between different parts of a molecule is called **polarity**. A polar molecule is a molecule in which part of the molecule is positively charged and part of the molecule is negatively charged.

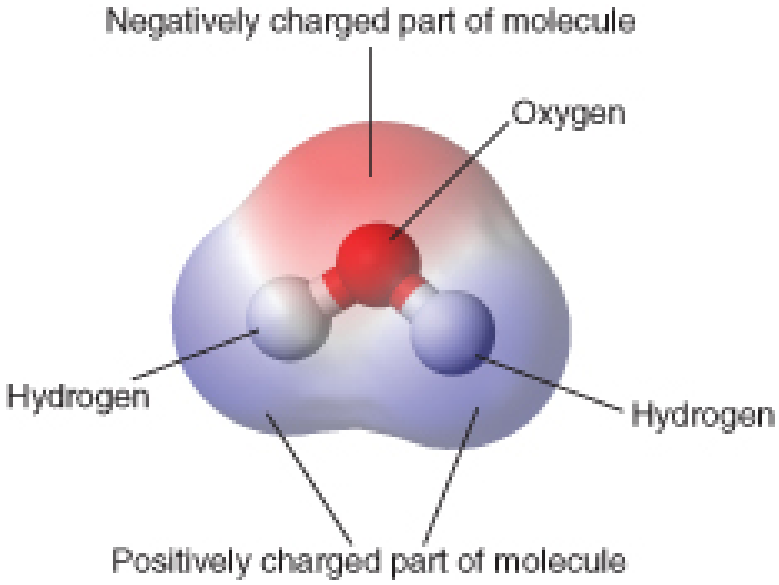

Figure 2.21: This model shows the arrangement of oxygen and hydrogen atoms in a water molecule. The nucleus of the oxygen atom attracts electrons more strongly than do the hydrogen nuclei. As a result, the middle part of the molecule near oxygen has a negative charge, and the other parts of the molecule have a positive charge. In essence, the electrons are "pulled" toward the nucleus of the oxygen atom and away from the hydrogen atom nuclei. Water is a polar molecule, with an unequal distribution of charge throughout the molecule.

Opposite electrical charges attract one another other. Therefore, the positive part of one water molecule is attracted to the negative parts of other water molecules. Because of this attraction, bonds form between hydrogen and oxygen atoms of adjacent water molecules, as demonstrated in **Figure** 2.22. This type of bond always involves a hydrogen atom, so it is called a **hydrogen bond**. Hydrogen bonds are bonds between molecules, and they are not as strong as bonds within molecules. Nonetheless, they help hold water molecules together.

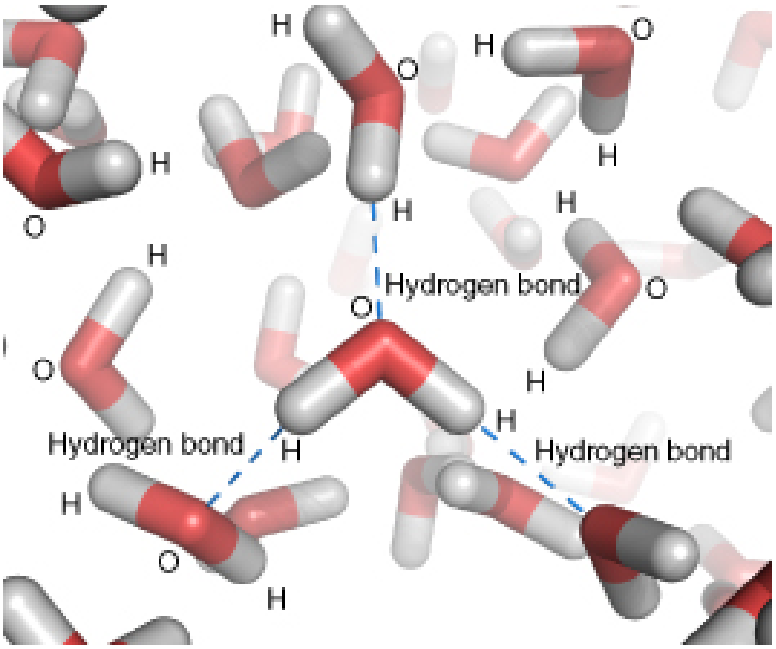

Figure 2.22: Hydrogen bonds form between positively and negatively charged parts of water molecules. The bonds hold the water molecules together.

Hydrogen bonds can also form within a single large organic molecule (see the *Organic Compounds* lesson). For example, hydrogen bonds that form between different parts of a protein molecule bend the molecule into a distinctive shape, which is important for the protein's functions. Hydrogen bonds also hold together the two nucleotide chains of a DNA molecule.

Sticky, Wet Water

Water has some unusual properties due to its hydrogen bonds. One property is the tendency for water molecules to stick together. For example, if you drop a tiny amount of water onto a very smooth surface, the water molecules will stick together and form a droplet, rather than spread out over the surface. The same thing happens when water slowly drips from a leaky faucet. The water doesn't fall from the faucet as individual water molecules but as droplets of water. The tendency of water to stick together in droplets is also illustrated by the dew drops in **Figure** 2.23.

Figure 2.23: Droplets of dew cling to a spider web, demonstrating the tendency of water molecules to stick together because of hydrogen bonds.

Hydrogen bonds also explain why water's boiling point (100° C) is higher than the boiling points of similar substances without hydrogen bonds. Because of water's relatively high boiling point, most water exists in a liquid state on Earth. Liquid water is needed by all living organisms. Therefore, the availability of liquid water enables life to survive over much of the planet.

Density of Ice and Water

The melting point of water is 0° C. Below this temperature, water is a solid (ice). Unlike most chemical substances, water in a solid state has a lower density than water in a liquid state. This is because water expands when it freezes. Again, hydrogen bonding is the reason. Hydrogen bonds cause water molecules to line up less efficiently in ice than in liquid water. As a result, water molecules are spaced farther apart in ice, giving ice a lower density than liquid water. A substance with lower density floats on a substance with higher density. This explains why ice floats on liquid water, whereas many other solids sink to the bottom of liquid water.

In a large body of water, such as a lake or the ocean, the water with the greatest density always sinks to the bottom. Water is most dense at about 4° C. As a result, the water at the bottom of a lake or the ocean usually has temperature of about 4° C. In climates with cold winters, this layer of 4° C water insulates the bottom of a lake from freezing temperatures. Lake organisms such as fish can survive the winter by staying in this cold, but unfrozen, water at the bottom of the lake.

Solutions

Water is one of the most common ingredients in solutions. A **solution** is a homogeneous mixture composed of two or more substances. In a solution, one substance is dissolved in another substance, forming a mixture that has the same proportion of substances throughout. The dissolved substance in a solution is called the **solute**. The substance in which is it dissolved is called the **solvent**. An example of a solution in which water is the solvent is salt water. In this solution, a solid—sodium chloride—is the solute. In addition to a solid dissolved in a liquid, solutions can also form with solutes and solvents in other states of matter. Examples are given in **Table 1**.

Table 2.3: **Solutions commonly form when a solid solute dissolves in a liquid solvent. However, solutions can form with solutes and solvents in any of the three major states of matter.**

Solvent	Gas	Liquid	Solid
Gas	Oxygen and other gases in nitrogen (air)		
Liquid	Carbon dioxide in water (carbonated water)	Ethanol (an alcohol) in water	Sodium chloride in water (salt water)
Solid	Hydrogen in metals	Mercury in silver and other metals (dental fillings)	Iron in carbon (steel)

(*Source:* http://en.wikipedia.org/wiki/Solute, *License:* Creative Commons)

The ability of a solute to dissolve in a particular solvent is called **solubility**. Many chemical substances are soluble in water. In fact, so many substances are soluble in water that water is called the universal solvent. Water is a strongly polar solvent, and polar solvents are better at dissolving polar solutes. Many organic compounds and other important biochemicals are polar, so they dissolve well in water. On the other hand, strongly polar solvents like water cannot dissolve strongly nonpolar solutes like oil. Did you ever try to mix oil and water? Even after being well shaken, the two substances quickly separate into distinct layers.

Acids and Bases

Water is the solvent in solutions called acids and bases. To understand acids and bases, it is important to know more about pure water, in which nothing is dissolved. In pure water (such as distilled water), a tiny fraction of water molecules naturally breaks down, or dissociates, to form ions. An **ion** is an electrically charged atom or molecule. The dissociation of pure

water into ions is represented by the chemical equation:

$2\ H_2O \rightarrow H_3O^+ + OH^-$.

The products of this reaction are a hydronium ion (H_3O^+) and a hydroxide ion (OH^-). The hydroxide ion is negatively charged. It forms when a water molecule donates, or gives up, a positively charged hydrogen ion. The hydronium ion, modeled in **Figure** 2.24, is positively charged. It forms when a water molecule accepts a positively charged hydrogen ion (H^+).

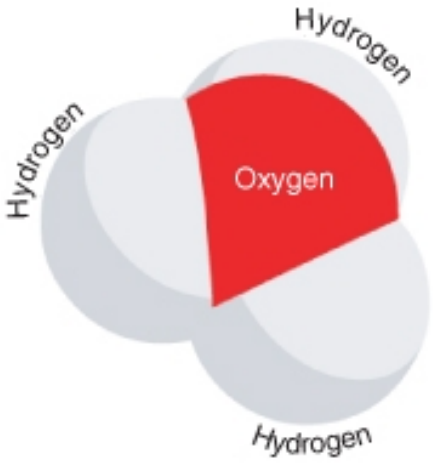

Figure 2.24: A hydronium ion has the chemical formula HO. The plus sign () indicates that the ion is positively charged. How does this molecule differ from the water molecule in ?

Acidity and pH

Acidity refers to the hydronium ion concentration of a solution. It is measured by **pH**. In pure water, the hydronium ion concentration is very low. Only about one in ten million water molecules naturally dissociates to form a hydronium ion in pure water. This gives water a pH of 7. The hydronium ions in pure water are also balanced by hydroxide ions, so pure water is neutral (neither an acid nor a base).

Because pure water is neutral, any other solution with the same hydronium ion concentration and pH is also considered to be neutral. If a solution has a higher concentration of hydronium ions and lower pH than pure water, it is called an **acid**. If a solution has a lower concentration of hydronium ions and higher pH than pure water, it is called a **base**. Several acids and bases

and their pH values are identified on the pH scale, which ranges from 0 to 14, in **Figure** 2.25.

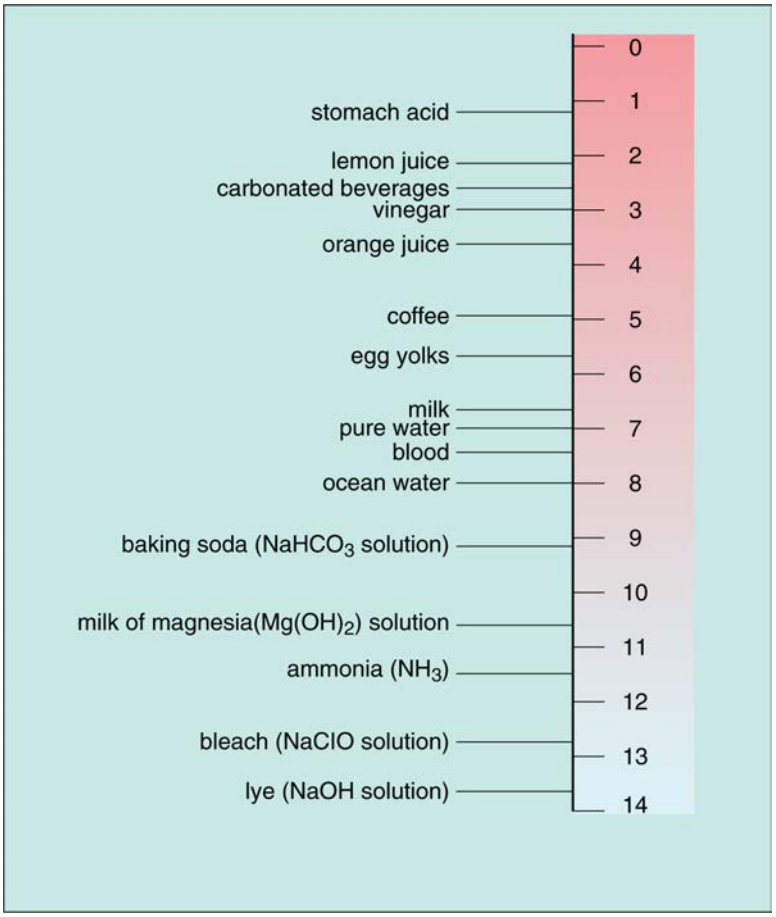

Figure 2.25: Water has a pH of 7, so this is the point of neutrality on the pH scale. Acids have a pH less than 7, and bases have a pH greater than 7.

The pH scale is a negative logarithmic scale. Because the scale is negative, as the ion concentration increases, the pH value decreases. In other words, the more acidic the solution, the lower the pH value. Because the scale is logarithmic, each one-point change in pH reflects a ten-fold change in the hydronium ion concentration and acidity. For example, a solution with a pH of 6 is ten times as acidic as pure water with a pH of 7.

Acids

An acid can be defined as a hydrogen ion donor. The hydrogen ions bond with water molecules, leading to a higher concentration of hydronium ions than in pure water. For example, when hydrochloric acid (HCl) dissolves in pure water, it donates hydrogen ions

(H^+) to water molecules, forming hydronium ions (H_3O^+) and chloride ions (Cl^-). This is represented by the chemical equation:

$HCl + H_2O \rightarrow Cl^- + H_3O^+$.

Strong acids can be harmful to organisms and damaging to materials. Acids have a sour taste and may sting or burn the skin. Testing solutions with litmus paper is an easy way to identify acids. Acids turn blue litmus paper red.

Bases

A base can be defined as a hydrogen ion acceptor. It accepts hydrogen ions from hydronium ions, leading to a lower concentration of hydronium ions than in pure water. For example, when the base ammonia (NH_3) dissolves in pure water, it accepts hydrogen ions (H^+) from hydronium ions (H_3O^+) to form ammonium ions (NH_4^+) and hydroxide ions (OH^-). This is represented by the chemical equation:

$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$.

Like strong acids, strong bases can be harmful to organisms and damaging to materials. Bases have a bitter taste and feel slimy to the touch. They can also burn the skin. Bases, like acids, can be identified with litmus paper. Bases turn red litmus paper blue.

Neutralization

What do you think would happen if you mixed an acid and a base? If you think the acid and base would "cancel each other out," you are right. When an acid and base react, they form a neutral solution of water and a salt (a molecule composed of a positive and negative ion). This type of reaction is called a **neutralization** reaction. For example, when the base sodium hydroxide (NaOH) and hydrochloric acid (HCl) react, they form a neutral solution of water and the salt sodium chloride (NaCl). This reaction is represented by the chemical equation:

$NaOH + HCl \rightarrow NaCl + H_2O$.

In this reaction, hydroxide ions (OH^-) from the base combine with hydrogen ions (H^+) from the acid to form water. The other ions in the solution (Na^+) and (Cl^-) combine to form sodium chloride.

Acids and Bases in Organisms

Enzymes are needed to speed up biochemical reactions. Most enzymes require a specific range of pH in order to do their job. For example, the enzyme pepsin, which helps break down proteins in the human stomach, requires a very acidic environment in order to function.

Strong acid is secreted into the stomach, allowing pepsin to work. Once the contents of the stomach enter the small intestine, where most digestion occurs, the acid must be neutralized. This is because enzymes that work in the small intestine need a basic environment. An organ near the small intestine, called the pancreas, secretes bicarbonate ions (HCO_3^-) into the small intestine to neutralize the stomach acid.

Bicarbonate ions play an important role in neutralizing acids throughout the body. Bicarbonate ions are especially important for protecting tissues of the central nervous system from changes in pH. The central nervous system includes the brain, which is the body's control center. If pH deviates too far from normal, the central nervous system cannot function properly. This can have a drastic effect on the rest of the body.

Water and Life

Humans are composed of about 70 percent water (not counting water in body fat). This water is crucial for normal functioning of the body. Water's ability to dissolve most biologically significant compounds—from inorganic salts to large organic molecules—makes it a vital solvent inside organisms and cells.

Water is an essential part of most metabolic processes within organisms. **Metabolism** is the sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions). In anabolic reactions, water is generally removed from small molecules in order to make larger molecules. In catabolic reactions, water is used to break bonds in larger molecules in order to make smaller molecules.

Water is central to two related, fundamental metabolic reactions in organisms: photosynthesis (*Photosynthesis* chapter) and respiration (*Cellular Respiration* chapter). All organisms depend directly or indirectly on these two reactions.

- In photosynthesis, cells use the energy in sunlight to change water and carbon dioxide into glucose and oxygen. This is an anabolic reaction, represented by the chemical equation:

$$6\ CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_{6,} + 6\ O_2.$$

- In cellular respiration, cells break down glucose in the presence of oxygen and release energy, water, and carbon dioxide. This is a catabolic reaction, represented by the chemical equation:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$$

Two other types of reactions that occur in organisms and involve water are dehydration and hydration reactions. A dehydration reaction occurs when molecules combine to form a

single, larger molecule and also a molecule of water. (If some other small molecule is formed instead of water, the reaction is called by the more general term, condensation reaction.) It is a type of catabolic reaction. An example of a dehydration reaction is the formation of peptide bonds between amino acids in a polypeptide chain. When two amino acids bond together, a molecule of water is lost. This is shown in **Figure** 2.26.

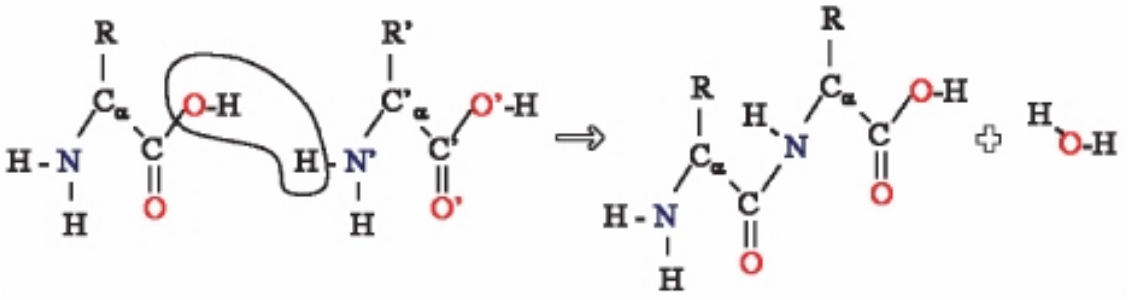

Figure 2.26: In this dehydration reaction, two amino acids form a peptide bond. A water molecule also forms.

A hydration reaction is the opposite of a dehydration reaction. A hydration reaction adds water to an organic molecule and breaks the large molecule into smaller molecules. Hydration reactions occur in an acidic water solution. An example of hydration reaction is the breaking of peptide bonds in polypeptides. A hydroxide ion (OH-) and a hydrogen ion (H+) (both from a water molecule) bond to the carbon atoms that formed the peptide bond. This breaks the peptide bond and results in two amino acids.

Water is essential for all of these important chemical reactions in organisms. As a result, virtually all life processes depend on water. Clearly, without water, life as we know it could not exist.

Lesson Summary

- Most of Earth's water is salt water located on the planet's surface. Water is constantly recycled through the water cycle.
- Water molecules are polar, so they form hydrogen bonds. This gives water unique properties, such as a relatively high boiling point.
- A solution is a homogeneous mixture in which a solute dissolves in a solvent. Water is a very common solvent, especially in organisms.

- The ion concentration of neutral, pure water gives water a pH of 7 and sets the standard for defining acids and bases. Acids have a pH lower than 7, and bases have a pH higher than 7.
- Water is essential for most life processes, including photosynthesis, cellular respiration, and other important chemical reactions that occur in organisms.

Review Questions

1. Where is most of Earth's water?
2. What is polarity, and why is water polar?
3. Define solution, and give an example of a solution.
4. What is the pH of a neutral solution? Why?
5. Draw a circle diagram to represent the water cycle. Identify the states of water and the processes in which water changes state throughout the cycle.
6. What type of reaction is represented by the chemical equation below? Defend your answer. $KOH + HCl \rightarrow KCl + H_2O$
7. Explain how hydrogen bonds cause molecules of liquid water to stick together.
8. Summarize how metabolism in organisms depends on water.

Further Reading / Supplemental Links

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- Robert A. Copeland, Enzymes: A Practical Introduction to Structure, Mechanisms, and Data Analysis. Wiley, 2000.
- Peter Swanson, Water: The Drop of Life. Cowles Creative Publishing, 2001.
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Vocabulary

acid Solution with a higher hydronium ion concentration than pure water and a pH lower than 7.

acidity Hydronium ion concentration of a solution.

base Solution with a lower hydronium ion concentration than pure water and a pH higher than 7.

condensation Process in which water vapor changes to water droplets, forming clouds or fog.

evaporation Process in which liquid water changes into water vapor.

hydrogen bond Bond that forms between a hydrogen atom in one molecule and a different atom in another molecule.

ion Electrically charged atom or molecule.

metabolism Sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions).

neutralization Chemical reaction in which an acid and a base react to form a neutral solution of water and a salt.

pH Measure of the acidity, or hydronium ion concentration, of a solution.

polarity Difference in electrical charge between different parts of a molecule.

precipitation Rain, snow, sleet, or other type of moisture that falls from clouds.

solubility Ability of a solute to dissolve in a particular solvent.

solute Substance in a solution that is dissolved by the other substance (the solvent).

solution Homogeneous mixture in which one substance is dissolved in another.

solvent Substance in a solution that dissolves the other substance (the solute).

sublimation Process in which snow or ice changes directly into water vapor.

transpiration Process in which plants give off water, most of which evaporates.

Points to Consider

Most life processes take place within cells. You probably know that cells are the microscopic building blocks of organisms.

- What do you think you would see if you could look inside a cell?
- What structures might you see?
- What processes might you observe?

Image Sources

(1) http://en.wikipedia.org/wiki/Image:2-amino-acidsb.png. Public Domain.

(2) http://en.wikipedia.org/wiki/Image:Water_molecule.svg. Creative Commons.

(3) http://en.wikipedia.org/wiki/Image:Water_drops_on_spider_web.jpg. Public Domain.

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(26) http://en.wikipedia.org/wiki/Image:AminoAcidball.svg. Creative Commons.

Chapter 3

Cell Structure and Function

3.1 Lesson 3.1: Introduction to Cells

Lesson Objectives

- Identify the scientists that first observed cells.
- Outline the importance of microscopes in the discovery of cells.
- Summarize what the cell theory proposes.
- Identify the limitations on cell size.
- Identify the three parts common to all cells.
- Compare prokaryotic and eukaryotic cells.

Introduction

Knowing the make up of cells and how cells work is necessary to all of the biological sciences. Learning about the similarities and differences between cell types is particularly important to the fields of cell biology and molecular biology. The importance of the similarities and differences between cell types is a unifying theme in biology. They allow the principles learned from studying one cell type to be applied when learning about other cell types. For example, learning about how single-celled animals or bacteria work can help us understand more about how human cells work. Research in cell biology is closely linked to genetics, biochemistry, molecular biology, and developmental biology.

Discovery of Cells

A **cell** is the smallest unit that can carry out the processes of life. It is the basic unit of all living things, and all organisms are made up of one or more cells. In addition to having

the same basic structure, all cells carry out similar life processes. These include transport of materials, obtaining and using energy, waste disposal, replication, and responding to their environment.

If you look at living organisms under a microscope you will see they are made up of cells. The word cell was first used by Robert Hooke, a British biologist and early microscopist. Hooke looked at thin slices of cork under a microscope. The structure he saw looked like a honeycomb as it was made up of many tiny units. Hooke's drawing is shown in **Figure** 3.1. In 1665 Hooke published his book *Micrographia,* in which he wrote:

> ... I could exceedingly plainly perceive it to be all perforated and porous, much like a Honey-comb, but that the pores of it were not regular.... these pores, or cells, ... were indeed the first *microscopical* pores I ever saw, and perhaps, that were ever seen, for I had not met with any Writer or Person, that had made any mention of them before this...

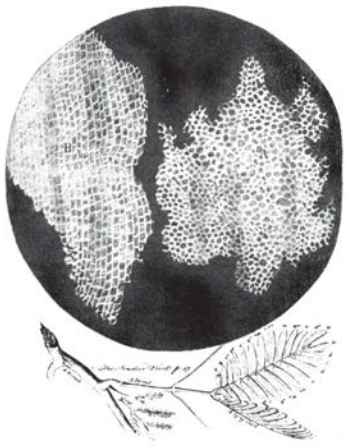


Figure 3.1: Drawing of the structure of cork from as it appeared under the microscope to Robert Hooke. The first scientific use of the word appears in this book.

During the 1670s, the Dutch tradesman Antony van Leeuwenhoek, shown in **Figure** 3.2, used microscopes to observe many microbes and body cells. Leeuwenhoek developed an interest in microscopy and ground his own lenses to make simple microscopes. Compound microscopes, which are microscopes that use more than one lens, had been invented around 1595. Several people, including Robert Hooke, had built compound microscopes and were making important discoveries with them during Leeuwenhoek's time. These compound microscopes were very similar to the microscopes in use today. However, Leeuwenhoek was so good at making lenses that his simple microscopes were able to magnify much more clearly

than the compound microscopes of his day. His microscope's increased ability to magnify over 200 times is comparable to a modern compound light microscope.

Leeuwenhoek was also very curious, and he took great care in writing detailed reports of what he saw under his microscope. He was the first person to report observations of many microscopic organisms. Some of his discoveries included tiny animals such as ciliates, foraminifera, roundworms, and rotifers, shown in **Figure** 3.3. He discovered blood cells and was the first person to see living sperm cells. In 1683, Leeuwenhoek wrote to the Royal Society of London about his observations on the plaque between his own teeth, "a little white matter, which is as thick as if 'twere batter." He called the creatures he saw in the plaque *animacules,* or tiny animals. This report was among the first observations on living bacteria ever recorded.

Figure 3.2: Antony van Leeuwenhoek (1632-1723). His carefully crafted microscopes and insightful observations of microbes led to the title the "Father of Microscopy."

Figure 3.3: Rotifers, similar to the type that Leeuwenhoek saw under his microscope.

Microscopes

Hooke's and Leeuwenhoek's studies and observations filled people with wonder because their studies were of life forms that were everywhere, but too small to see with the naked eye. Just think how amazed you would be if you were to read about the first accounts of a newly discovered microorganism from the moon or Mars. Your first thought might be "Things can live there?!" which was probably the first thought of the people who read Hooke's and Leeuwenhoek's accounts. The microscope literally opened up an amazing new dimension in the natural sciences, and became a critical tool in the progress of biology.

Magnifying glasses had been in use since the 1300s, but the use of lenses to see very tiny objects was a slowly-developing technology. The magnification power of early microscopes was very limited by the glass quality used in the lenses and the amount of light reflected off the object. These early light microscopes had poor resolution and a magnification power of about 10 times. Compare this to the over 200 times magnification that Leeuwenhoek was able to achieve by carefully grinding his own lenses. However, in time the quality of microscopes was much improved with better lighting and resolution. It was through the use of light microscopes that the first discoveries about the cell and the cell theory (1839) were developed.

However, by the end of the 19^{th} century, light microscopes had begun to hit resolution limits. **Resolution** is a measure of the clarity of an image; it is the minimum distance that two points can be separated by and still be distinguished as two separate points. Because light beams have a physical size, it is difficult to see an object that is about the same size as the wavelength of light. Objects smaller than about 0.2 micrometers appear fuzzy, and objects below that size just cannot be seen. Light microscopes were still useful, but most of the organelles and tiny cell structures discussed in later lessons were invisible to the light microscope.

In the 1950s, a new system was developed that could use a beam of electrons to resolve very tiny dimensions at the molecular level. Electron microscopes, one of which is shown in **Figure** 3.4, have been used to produce images of molecules and atoms. They have been used to visualize the tiny sub-cellular structures that were invisible to light microscopes. Many of the discoveries made about the cell since the 1950s have been made with electron microscopes.

The Cell Theory

Later, biologists found cells everywhere. Biologists in the early part of the 19th century suggested that all living things were made of cells, but the role of cells as the primary building block of life was not discovered until 1839 when two German scientists, Theodor Schwann, a zoologist, and Matthias Jakob Schleiden, a botanist, suggested that cells were the basic unit of all living things. Later, in 1858, the German doctor Rudolf Virchow observed

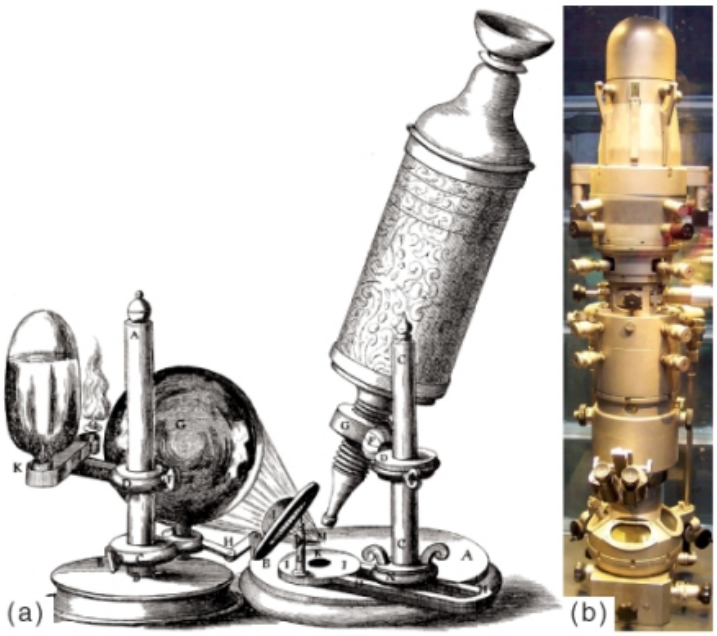


Figure 3.4: Left to right: (a) Hooke's light microscope (b) Modern electron microscope.

that cells divide to produce more cells. He proposed that all cells arise only from other cells. The collective observations of all three scientists form the *cell theory*. The modern cell theory states that:

- All organisms are made up of one or more cells.
- All the life functions of an organism occur within cells.
- All cells come from preexisting cells.

As with any theory, the cell theory is based on observations that over many years upheld the basic conclusions of Schwann's paper written in 1839. However, one of Schwann's original conclusions stated that cells formed in a similar way to crystals. This observation, which refers to *spontaneous generation* of life, was discounted when Virchow proposed that all cells arise only from other cells. The cell theory has withstood intense examination of cells by modern powerful microscopes and other instruments. Scientists use new techniques and equipment to look into cells to discover additional explanations for how they work.

Diversity of Cells

Different cells within a single organism can come in a variety of sizes and shapes. They may not be very big, but their shapes can be very different from each other. However, these cells

all have common abilities, such as getting and using food energy, responding to the external environment, and reproducing. A cell's shape determines its function.

Cell Size

If cells have such an important job, why are they so small? And why are there no organisms with huge cells? The answers to these questions lie in a cell's need for fast, easy food. The need to be able to pass nutrients and gases into and out of the cell sets a limit on how big cells can be. The larger a cell gets, the more difficult it is for nutrients and gases to move in and out of the cell.

As a cell grows, its volume increases more quickly than its surface area. If a cell was to get very large, the small surface area would not allow enough nutrients to enter the cell quickly enough for the cell's needs. This idea is explained in **Figure** 3.5. However, large cells have a way of dealing with some size challenges. Big cells, such as some white blood cells, often grow more nuclei so that they can supply enough proteins and RNA for the cell's needs. Large, metabolically active cells often have lots of folds in their cell surface membrane. These folds increase the surface area available for transport into or out of the cell. Such cell types are found lining your small intestine, where they absorb nutrients from your food through little folds called *microvilli*.

Scale of Measurements

1 centimeter (cm) = 10 millimeters (mm) = 10^{-2} meters (m)

1 mm = 1000 micrometers (µm) = 10^{-3} m

1 µm = 1000 nanometers (nm) = 10^{-6} m

1 nm = 10^{-3} µm

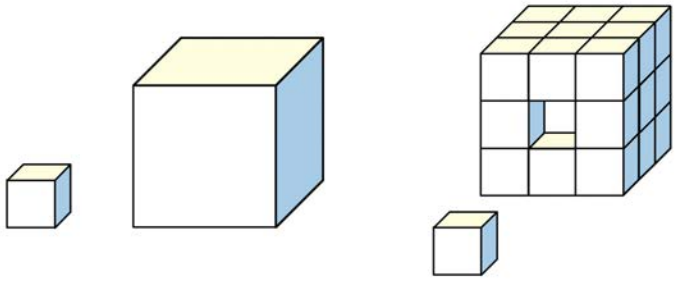


Figure 3.5: A small cell (left), has a larger surface-area to volume ratio than a bigger cell (center). The greater the surface-area to volume ratio of a cell, the easier it is for the cell to get rid of wastes and take in essential materials such as oxygen and nutrients.

Imagine cells as little cube blocks. A small cube cell is one unit in length.

The total surface area of this cell is calculated by the equation:

height × width × number of sides × number of boxes

$1 \times 1 \times 6 \times 1 = 6$

The volume of the cell is calculated:

height x width x length x number of boxes

$1 \times 1 \times 1 \times 1 = 1$

The surface-area to volume ratio is:

area ÷ volume

$6 \div 1 = 6$

A larger cell that is 3 units in length would have a total surface area of

$3 \times 3 \times 6 \times 1 = 54$

and a volume of:

$3 \times 3 \times 3 \times 1 = 27$

The surface-area to volume ratio of the large cell is:

$54 \div 27 = 2$

Now, replace the three unit cell with enough one unit cells to equal the volume of the single three unit cell. This can be done with 27 one unit cells. Find the total surface area of the 27 cells:

$1 \times 1 \times 6 \times 27 = 162$ units

The total volume of the block of 27 cells is:

$1 \times 1 \times 1 \times 27 = 27$

The surface-area to volume ratio of the 27 cells is:

$162 \div 27 = 6$

An increased surface area to volume ratio means increased exposure to the environment. This means that nutrients and gases can move in and out of a small cell more easily than in and out of a larger cell.

The smallest prokaryotic cell currently known has a diameter of only 400 nm. Eukaryotic cells normally range between 1– 100 µm in diameter.

The cells you have learned about so far are tinier than the period at the end of this sentence, so they are normally measured on a very tiny scale. Most cells are between 1 and 100 µm in diameter. The mouse cells in **Figure** 3.6 are about 10 µm in diameter. One exception

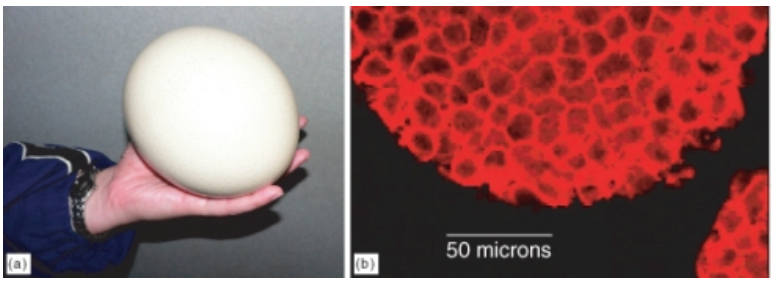


Figure 3.6: Ostrich eggs (a) can weigh as much as 1.5 kg, and be 13 cm in diameter, whereas each of the mouse cells (b) shown at right are each about 10 µm in diameter, much smaller than the period at the end of this sentence.

however, is eggs. Eggs contain the largest known single cell, and the ostrich egg is the largest of them all. The ostrich egg in **Figure** 3.6 is over 10,000 times larger than the mouse cell.

Cell Shape

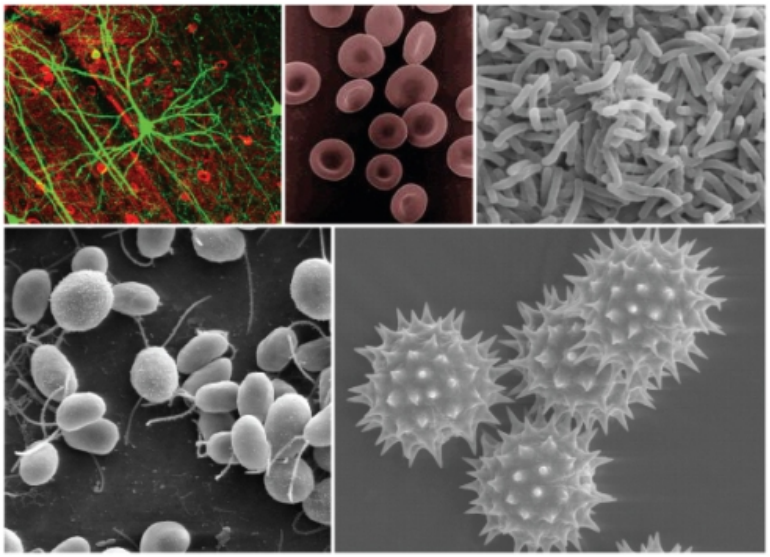


Figure 3.7: Cells come in very different shapes. Left to right, top row: Long, thin nerve cells; biconcave red blood cells; curved-rod shaped bacteria. Left to right, bottom row: oval, flagellated algae and round, spiky pollen grains are just a sample of the many shapes.

The variety of cell shapes seen in prokaryotes and eukaryotes reflects the functions that each cell has. Each cell type has evolved a shape that best helps it survive and do its job. For example, the nerve cell in **Figure** 3.7 has long, thin extensions that reach out to other nerve cells. The extensions help the nerve cell pass chemical and electrical messages quickly through the body. The spikes on the pollen grain help it stick to a pollinating insect or

animal so that it can be transferred to and pollinate another flower. The long whip-like flagella (tails) of the algae *Chlamydomonas* help it swim in water.

Parts of a Cell

There are many different types of cells, but all cells have a few things in common. These are:

- a cell or plasma membrane
- cytoplasm
- ribosomes for protein synthesis
- DNA (genetic information)

The **cell membrane** is the physical boundary between the inside of the cell (intracellular) and its outside environment (extracellular). It acts almost like the "skin" of the cell. **Cytoplasm** is the general term for all of the material inside the cell. Cytoplasm is made up of *cytosol*, a watery fluid that contains dissolved particles and organelles. **Organelles** are structures that carry out specific functions inside the cell. **Ribosomes** are the organelles on which proteins are made. Ribosomes are found throughout the cytosol of the cell. All cells also have DNA. DNA contains the genetic information needed for building structures such as proteins and RNA molecules in the cell.

Two Types of Cells

There are two cell types: prokaryotes and eukaryotes. Prokaryotic cells are usually single-celled and smaller than eukaryotic cells. Eukaryotic cells are usually found in multicellular organisms, but there are some single-celled eukaryotes.

Prokaryotic Cells

The bacterium in **Figure** 3.8 is a prokaryote. **Prokaryotes** are organisms that do not have a cell nucleus nor any organelles that are surrounded by a membrane. Some cell biologists consider the term "organelle" to describe membrane-bound structures only, whereas other cell biologists define organelles as discrete structures that have a specialized function. Prokaryotes have ribosomes, which are not surrounded by a membrane but do have a specialized function, and could therefore be considered organelles. Most of the metabolic functions carried out by a prokaryote take place in the plasma membrane.

Most prokaryotes are unicellular and have a cell wall that adds structural support and acts as a barrier against outside forces. Some prokaryotes have an extra layer outside their cell wall called a capsule, which helps them stick to surfaces or to each other. Prokaryotic DNA

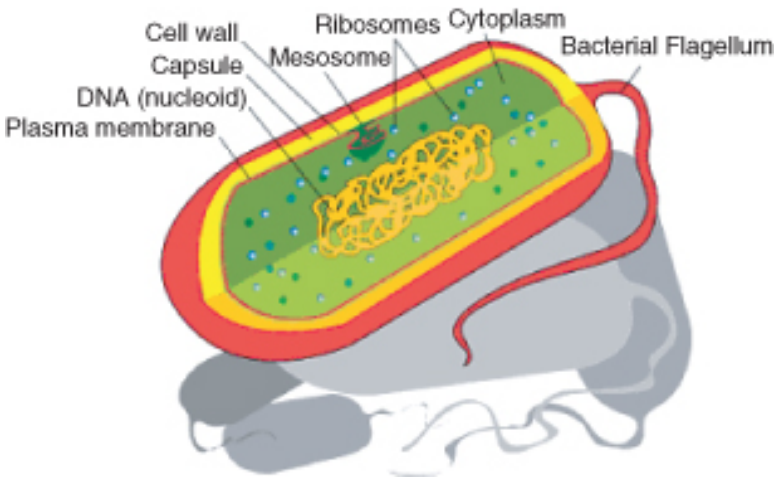


Figure 3.8: Diagram of a typical prokaryotic cell. Among other things, prokaryotic cells have a plasma membrane, cytoplasm, ribosomes, and DNA. Prokaryotes do not have membrane-bound organelles or a cell nucleus.

usually forms a circular molecule and is found in the cell's cytoplasm along with ribosomes. Prokaryotic cells are very small; most are between 1–10 µm in diameter. They are found living in almost every environment on Earth. Biologists believe that prokaryotes were the first type of cells on Earth and that they are the most common organisms on Earth today.

Eukaryotic Cells

A **eukaryote** is an organism whose cells are organized into complex structures by internal membranes and a cytoskeleton, as shown in **Figure** 3.13. The most characteristic membrane-bound structure of eukaryotes is the nucleus. This feature gives them their name, which comes from Greek and means "true nucleus." The **nucleus** is the membrane-enclosed organelle that contains DNA. Eukaryotic DNA is organized in one or more linear molecules, called chromosomes. Some eukaryotes are single-celled, but many are multicellular.

In addition to having a plasma membrane, cytoplasm, a nucleus and ribosomes, eukaryotic cells also contain membrane-bound organelles. Each organelle in a eukaryote has a distinct function. Because of their complex level of organization, eukaryotic cells can carry out many more functions than prokaryotic cells. The main differences between prokaryotic and eukaryotic cells are shown in **Figure** 3.11 and listed in **Table 1**. Eukaryotic cells may or may not have a cell wall. Plant cells generally have cell walls, while animal cells do not.

Eukaryotic cells are about 10 times the size of a typical prokaryote; they range between 10 and 100 µm in diameter while prokaryotes range between 1 and 10 µm in diameter, as shown in **Figure** 3.10. Scientists believe that eukaryotes developed about 1.6 – 2.1 billion years ago. The earliest fossils of multicellular organisms that have been found are 1.2 billion years

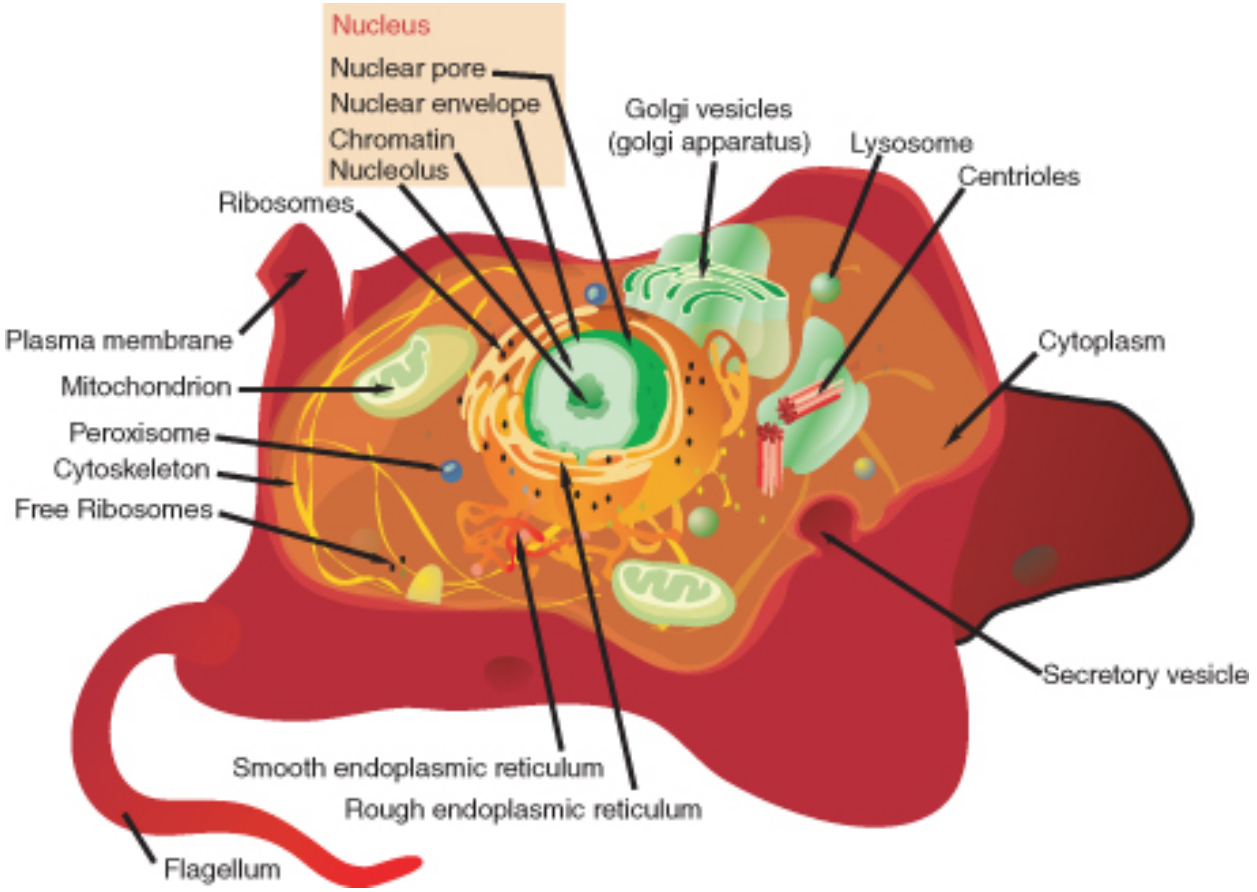


Figure 3.9: A eukaryotic cell, represented here by a model animal cell is much more complex than a prokaryotic cell. Eukaryotic cells contain many organelles that do specific jobs. No single eukaryotic cell has all the organelles shown here, and this model shows all eukaryotic organelles.

old.

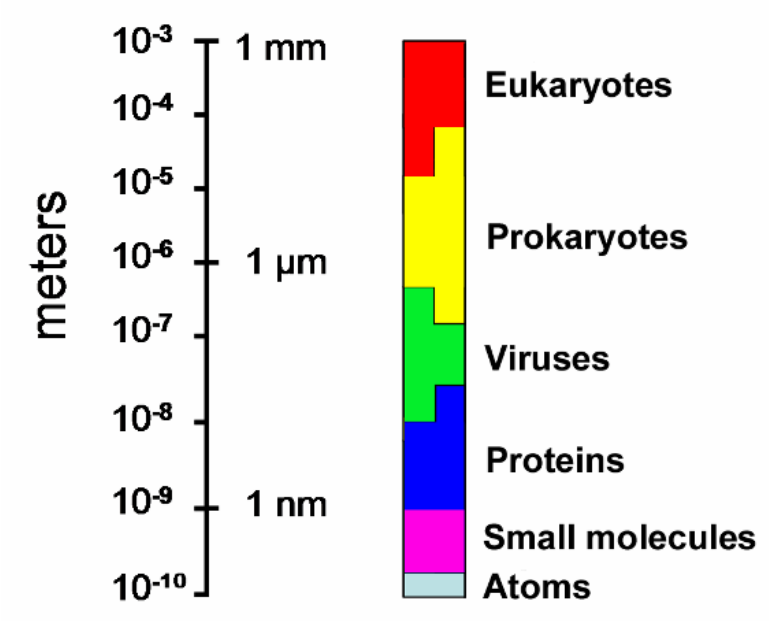


Figure 3.10: The relative scale of prokaryotic and eukaryotic cells. See how eukaryotic cells are generally 10 to 100 times larger than prokaryotic cells.

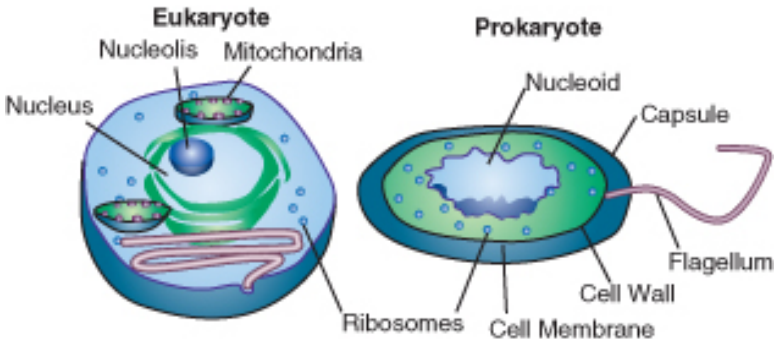


Figure 3.11: The main differences between prokaryotic and eukaryotic cells. Eukaryotic cells have membrane bound organelles while prokaryotic cells do not.

Table 3.1: **Structural Differences Between Prokaryotic Cells and Eukaryotic Cells**

Presence of	Prokaryote	Eukaryote
Plasma membrane	yes	yes
Genetic material (DNA)	yes	yes
Cytoplasm	yes	yes
Ribosomes	yes	yes

Table 3.1: (continued)

Presence of	Prokaryote	Eukaryote
Nucleus	no	yes
Nucleolus	no	yes
Mitochondria	no	yes
Other membrane-bound organelles	no	yes
Cell wall	yes	some (not around animal cells)
Capsule	yes	no
Average diameter	0.4 to 10 µm	1 to 100 µm

Are Viruses Prokaryotic or Eukaryotic?

Are viruses prokaryotic or eukaryotic? Neither. Viruses are not made up of cells, so they do not have a cell membrane or any cytoplasm, ribosomes, or other organelles. Viruses do not replicate by themselves, instead, they use their host cell to make more of themselves. So most virologists consider viruses non-living. But, they do evolve, which is a characteristic of living things.

A **virus** is a sub-microscopic particle that can infect living cells. Viruses are much smaller than prokaryotic organisms. In essence, a virus is simply a nucleic acid surrounded by a protein coat. Viruses will be discussed in more detail in the *Prokaryotes and Viruses* chapter.

Lesson Summary

- Robert Hooke first saw and named cells. Antony van Leeuwenhoek was the first person to see living cells.
- Before the development of microscopes, the existence of cellular life was unknown. The development of light microscopes and later electron microscopes helped scientists learn more about the cell. Most of the discoveries about cell structure since the 1950s have been made due to the use of electron microscopes.
- The cell theory states that all living things are made of one or more cells, that cells are the basic unit of life, and that cells come only from other cells.
- Cell size is limited by a cell's surface area to volume ratio. A cell's shape is determined by its function.
- Parts common to all cells are the plasma membrane, the cytoplasm, ribosomes, and genetic material.
- Prokaryotic cells lack a nucleus and other membrane-bound organelles.

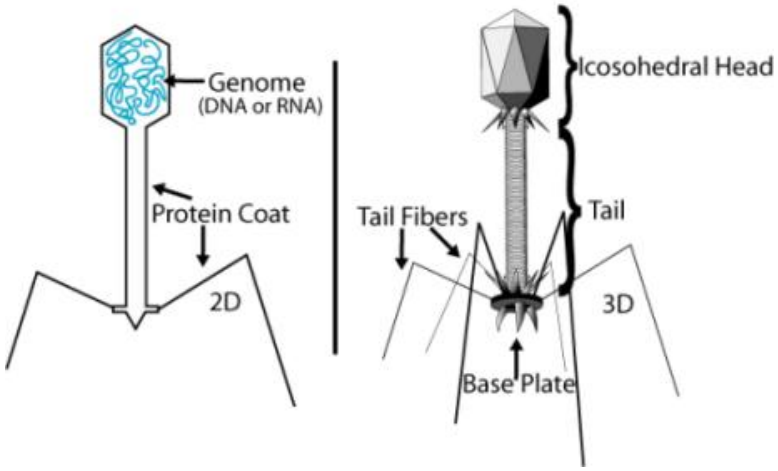


Figure 3.12: Structural overview of a virus, the T2 phage. A 2-dimensional representation is on the left, and a 3-dimensional representation is on the right. The virus is essentially nucleic acid surrounded by a protein coat.

Review Questions

1. Describe the contributions of Hooke and Leeuwenhoek to cell biology.
2. What enabled Leeuwenhoek to observe things that nobody else had seen before?
3. What three things does the cell theory propose?
4. A cell has a volume of 64 units, and total surface area of 96 units. What is the cell's surface area to volume ratio (surface area ÷ volume)?
5. What is the relationship between cell shape and function?
6. What are the three basic parts of a cell?
7. Compare prokaryotic and eukaryotic cells. Identify two differences between prokaryotic and eukaryotic cells.
8. Is the cell in this image prokaryotic or eukaryotic? Explain your answer.

Further Reading / Supplemental Links

- Human Anatomy © 2003 Martini, Timmons, Tallitsch. Published by Prentice Hall, Inc.
- http://www.ucmp.berkeley.edu/history/hooke.html
- http://www.ucmp.berkeley.edu/history/leeuwenhoek.html
- http://fig.cox.miami.edu/~cmallery/150/unity/cell.text.htm
- http://en.wikibooks.org/wiki/Cell_Biology/History
- http://en.wikibooks.org/wiki/General_Biology/Cells
- http://www.ucmp.berkeley.edu/history/hooke.html
- http://www.brianjford.com/wav-mict.htm

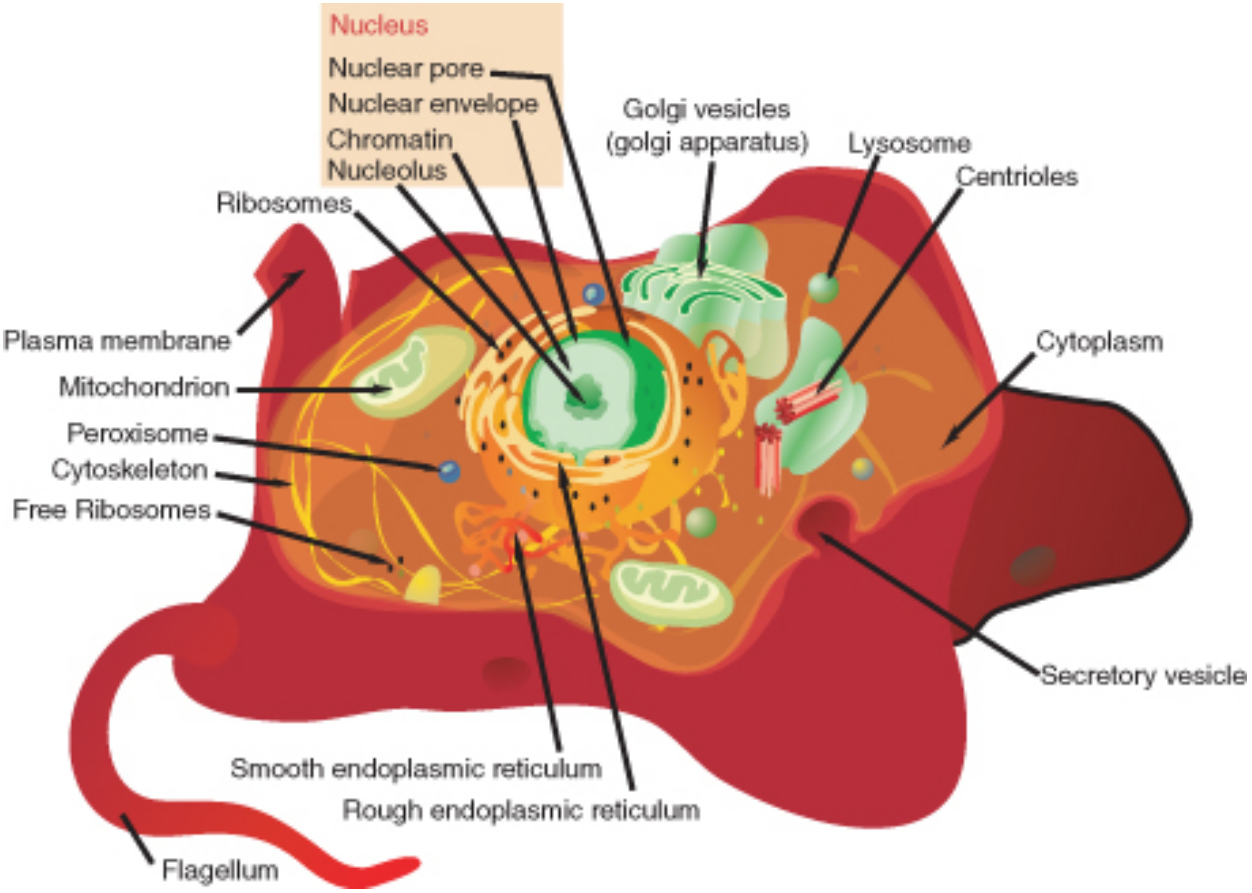

Nucleus
Nuclear pore
Nuclear envelope
Chromatin
Nucleolus
Ribosomes
Golgi vesicles
(golgi apparatus)
Lysosome
Centrioles
Plasma membrane
Mitochondrion
Peroxisome
Cytoskeleton
Free Ribosomes
Cytoplasm
Secretory vesicle
Smooth endoplasmic reticulum
Rough endoplasmic reticulum
Flagellum

Figure 3.13

- http://fig.cox.miami.edu/~cmallery/150/unity/cell.text.htm
- http://www.cellsalive.com/toc.htm
- http://publications.nigms.nih.gov/insidethecell/index.html
- http://cellimages.ascb.org/cdm4/browse.php?CISOROOT=/p4041coll11
- http://en.wikipedia.org

Vocabulary

cell The smallest unit that can carry out the processes of life; the basic unit of all living things.

cell membrane The physical boundary between the inside of the cell (intracellular) and its outside environment (extracellular).

cytoplasm The general term for all of the material inside the cell, between the cell membrane and the nucleus.

cytosol A watery fluid that contains dissolved particles and organelles; makes up cytoplasm.

DNA Deoxyribonucleic acid, the genetic material; contains the genetic information needed for building structures such as proteins.

eukaryote An organism whose cells are organized into complex structures by internal membranes and a cytoskeleton.

eukaryotic cells Typical of multi-celled organisms; have membrane bound organelles; usually larger than prokaryotic cells.

nucleus The membrane bound organelle that contains DNA; found in eukaryotic cells.

organelle Structure that carries out specific functions inside the cell.

prokaryotic cells Typical of simple, single-celled organisms, such as bacteria; lack a nucleus and other membrane bound organelles.

resolution A measure of the clarity of an image; the minimum distance that two points can be separated by and still be distinguished as two separate points.

ribosomes The organelles on which proteins are made (synthesized).

Points to Consider

Next we focus on cell structures and their roles.

- What do you think is the most important structure in a cell? Why?
- How do you think cells stay intact? What keeps the insides of a cell separate from the outside of the cell?

3.2 Lesson 3.2: Cell Structures

Lesson Objectives

- Outline the structure of the plasma membrane.
- Distinguish cytoplasm from cytosol.
- Name three types of protein fibers that make up the cytoskeleton.
- Distinguish between cilia and flagella.
- Identify three structures that plant cells have but animal cells do not.
- List three major organelles found only in eukaryotic cells and identify their roles.
- Distinguish between a colonial organism and a multicellular organism.
- Outline the relationship between cells, tissues, organs, and organ systems.

Introduction

The invention of the microscope opened up a previously unknown world. Before the invention of the microscope, very little was known about what made up living things and non-living things, or where living things came from. During Hooke's and Leeuwenhoek's time, spontaneous generation — the belief that living organisms grow directly from decaying organic substances — was the accepted explanation for the appearance of small organisms. For example, people accepted that mice spontaneously appeared in stored grain, and maggots formed in meat with no apparent external influence. Once cells were discovered, the search for answers to such questions as "what are cells made of?" and "what do they do?" became the focus of study.

Cell Function

Cells share the same needs: the need to get energy from their environment, the need to respond to their environment, and the need to reproduce. Cells must also be able to separate their relatively stable interior from the ever-changing external environment. They do this by coordinating many processes that are carried out in different parts of the cell. Structures that are common to many different cells indicate the common history shared by cell-based life.

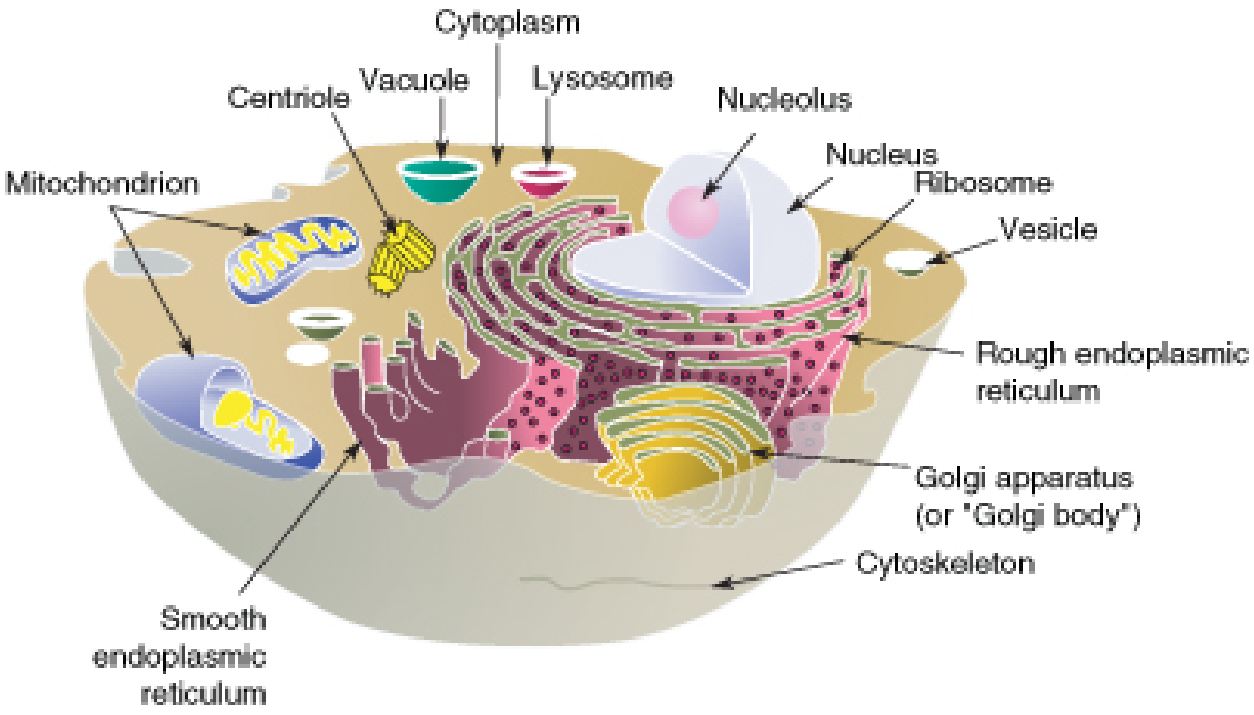


Figure 3.14: The structure and contents of a typical animal cell. Every animal cell has a cell membrane, cytoplasm, and a nucleus, but not all cells have every structure shown here. For example, some cells such as red blood cells do not have any mitochondria, yet others such as muscle cells may have thousands of mitochondria.

Examples of these common structures include the components of both the cell (or plasma) membrane and the cytoskeleton, and other structures shown in **Figure** 3.14.

Plasma Membrane

The plasma membrane (also called the cell membrane) has many functions. For example, it separates the internal environment of the cell from the outside environment. It allows only certain molecules into and out of the cell. The ability to allow only certain molecules in or out of the cell is referred to as **selective permeability** or **semipermeability**. These semipermeable membranes regulate the cell's interactions between the internal cytoplasm and the external surroundings. Proteins that are associated with the plasma membrane determine which molecules can pass through the membrane. This will be discussed in the next lesson. The plasma membrane also acts as the attachment point for both the intracellular cytoskeleton and, if present, the cell wall.

The plasma membrane is a lipid bilayer that is common to all living cells. A **lipid bilayer** is a double layer of closely-packed lipid molecules. The membranes of cell organelles are also lipid bilayers. The plasma membrane contains many different biological molecules, mostly lipids and proteins. These lipids and proteins are involved in many cellular processes.

Phospholipids

The main type of lipid found in the plasma membrane is phospholipid. A phospholipid is made up of a polar, phosphorus-containing head, and two long fatty acid, non-polar "tails." That is, the head of the molecule is hydrophilic (water-loving), and the tail is hydrophobic (water-fearing). Cytosol and extracellular fluid are made up of mostly water. In this watery environment, the water loving heads point out towards the water, and the water fearing tails point inwards, and push the water out. The resulting double layer is called a phospholipid bilayer. A **phospholipid bilayer** is made up of two layers of phospholipids, in which hydrophobic fatty acids are in the middle of the plasma membrane, and the hydrophilic heads are on the outside. An example of a simple phospholipid bilayer is illustrated in **Figure** 3.15.

Plasma membranes of eukaryotes contain many proteins, as well as other lipids called sterols. The proteins have various functions, such as channels that allow certain molecules into the cell and receptors that bind to signal molecules. In **Figure** 3.15, the smaller (green) molecules shown between the phospholipids are cholesterol molecules. Cholesterol helps keep the plasma membrane firm and stable over a wide range of temperatures. At least ten different types of lipids are commonly found in plasma membranes. Each type of cell or organelle will have a different percentage of each lipid, protein and carbohydrate.

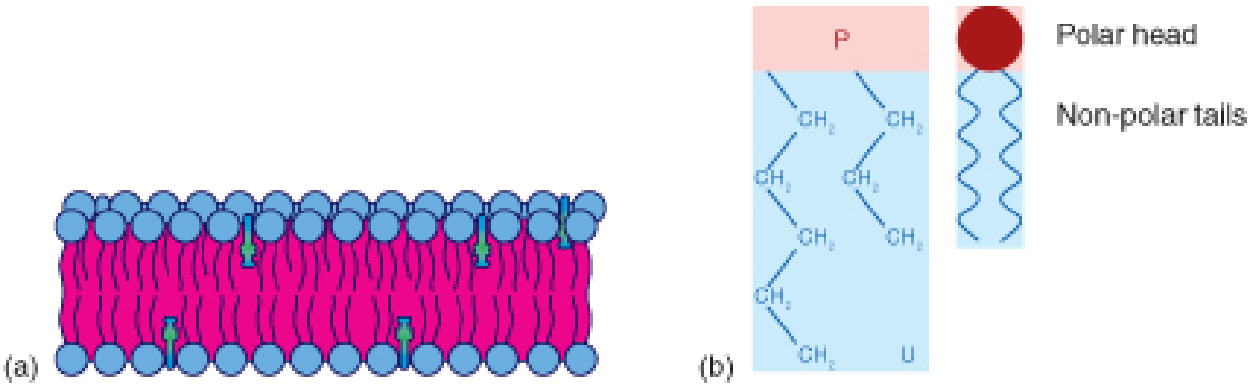


Figure 3.15: The hydrophobic fatty acids point towards the middle of the plasma membrane (pink), and the hydrophilic heads (blue) point outwards. The membrane is stabilized by cholesterol molecules (green). This self-organization of phospholipids results in a semipermeable membrane which allows only certain molecules in or out of the cell.

Membrane Proteins

Plasma membranes also contain certain types of proteins. A **membrane protein** is a protein molecule that is attached to, or associated with the membrane of a cell or an organelle. Membrane proteins can be put into two groups based on how the protein is associated with the membrane.

Integral membrane proteins are permanently embedded within the plasma membrane. They have a range of important functions. Such functions include channeling or transporting molecules across the membrane. Other integral proteins act as cell receptors. Integral membrane proteins can be classified according to their relationship with the bilayer:

- Transmembrane proteins span the entire plasma membrane. Transmembrane proteins are found in all types of biological membranes.
- Integral monotopic proteins are permanently attached to the membrane from only one side.

Some integral membrane proteins are responsible for cell adhesion (sticking of a cell to another cell or surface). On the outside of cell membranes and attached to some of the proteins are carbohydrate chains that act as labels that identify the cell type. Shown in **Figure** 3.16 are two different types of membrane proteins and associated molecules.

Peripheral membrane proteins are proteins that are only temporarily associated with the membrane. They can be easily removed, which allows them to be involved in cell signaling. Peripheral proteins can also be attached to integral membrane proteins, or they can stick into a small portion of the lipid bilayer by themselves. Peripheral membrane proteins are often associated with ion channels and transmembrane receptors. Most peripheral membrane proteins are hydrophilic.

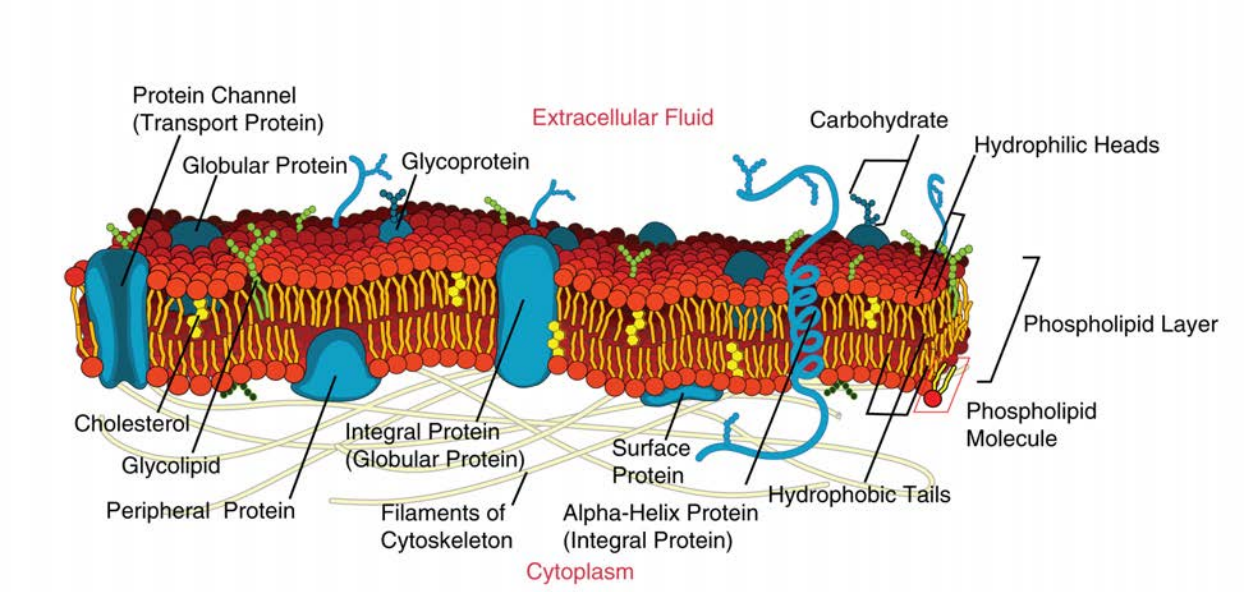


Figure 3.16: Some of the membrane proteins make up a major transport system that moves molecules and ions through the polar phospholipid bilayer.

Fluid Mosaic Model

In 1972 S.J. Singer and G.L. Nicolson proposed the now widely accepted Fluid Mosaic Model of the structure of cell membranes. The model proposes that integral membrane proteins are embedded in the phospholipid bilayer, as seen in **Figure** 3.16. Some of these proteins extend all the way through the bilayer, and some only partially across it. These membrane proteins act as transport proteins and receptors proteins.

Their model also proposed that the membrane behaves like a fluid, rather than a solid. The proteins and lipids of the membrane move around the membrane, much like buoys in water. Such movement causes a constant change in the "mosaic pattern" of the plasma membrane.

Cytoplasm

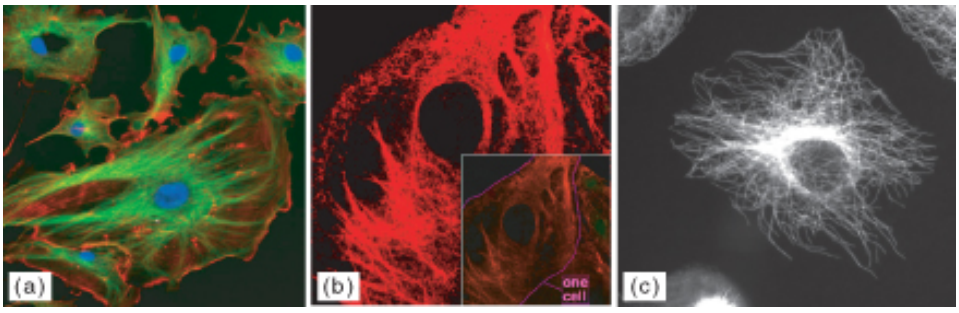
The gel-like material within the cell that holds the organelles is called **cytoplasm**. The cytoplasm plays an important role in a cell, serving as a "jelly" in which organelles are suspended and held together by a fatty membrane. The **cytosol**, which is the watery substance that does not contain organelles, is made up of 80% to 90% water.

The cytosol plays a mechanical role by exerting pressure against the cell's plasma membrane which helps keep the shape of the cell. Cytosol also acts as the site of biochemical reactions such as anaerobic glycolysis and protein synthesis. In prokaryotes all chemical reactions take place in the cytosol.

Cytoskeleton

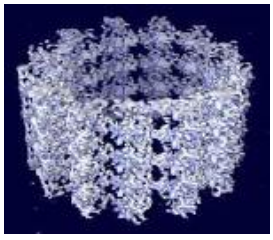
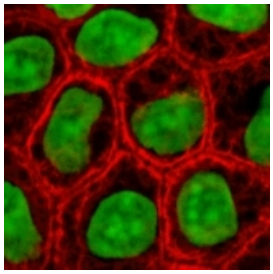
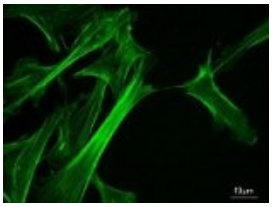
The **cytoskeleton** is a cellular "scaffolding" or "skeleton" that crisscrosses the cytoplasm. All eukaryotic cells have a cytoskeleton, and recent research has shown that prokaryotic cells also have a cytoskeleton. The eukaryotic cytoskeleton is made up of a network of long, thin protein fibers and has many functions. It helps to maintain cell shape. It holds organelles in place, and for some cells, it enables cell movement. The cytoskeleton also plays important roles in both the intracellular movement of substances and in cell division. Certain proteins act like a path that vesicles and organelles move along within the cell. The threadlike proteins that make up the cytoskeleton continually rebuild to adapt to the cell's constantly changing needs. Three main kinds of cytoskeleton fibers are microtubules, intermediate filaments, and microfilaments.

- **Microtubules**, shown in **Figure (a)**, are hollow cylinders and are the thickest of the cytoskeleton structures. They are most commonly made of filaments which are polymers of alpha and beta tubulin, and radiate outwards from an area near the nucleus called the centrosome. Tubulin is a protein that is composed of hollow cylinders which are made of two protein chains that are twisted around each other. Microtubules help keep cell shape. They hold organelles in place and allow them to move around the cell, and they form the mitotic spindle during cell division. Microtubules also make up parts of cilia and flagella, the organelles that help a cell to move.
- **Microfilaments**, shown in **Figure (b)**, are made of two thin actin chains that are twisted around one another. Microfilaments are mostly concentrated just beneath the cell membrane where they support the cell and help keep the cell's shape. Microfilaments form cytoplasmatic extentions such as pseudopodia and microvilli which allows certain cells to move. The actin of the microfilaments interacts with the protein myosin to cause contraction in muscle cells. Microfilaments are found in almost every cell, and are numerous in muscle cells and in cells that move by changing shape such as phagocytes (white blood cells that search the body for bacteria and other invaders).
- **Intermediate filament**, shown in **Figure (c)**, make-up differs from one cell type to another. Intermediate filaments organize the inside structure of the cell by holding organelles and providing strength. They are also structural components of the nuclear envelope. Intermediate filaments made of the protein keratin are found in skin, hair, and nails cells.



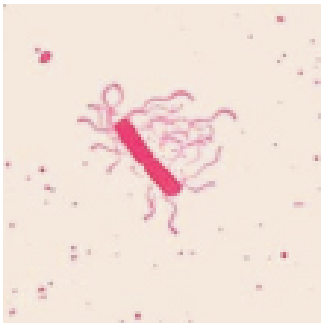
(a) The eukaryotic cytoskeleton. Microfilaments are shown in red, microtubules in green, and the nuclei are in blue. By linking regions of the cell together, the cytoskeleton helps support the shape of the cell. **(b)** Microscopy of keratin filaments (intermediate filaments) inside cells. **(c)** Microtubules in a methanol-fixated cell, visualized with anti-beta-tubuline antibodies.

Table 3.2: **Cytoskeleton Structure**

	Microtubules	Intermediate Filaments	Microfilaments
Fiber Diameter	About 25 nm	8 to 11 nm	Around 7 nm
Protein Composition	Tubulin, with two subunits, alpha and beta tubulin	One of different types of proteins such as lamin, vimentin, and keratin	Actin
Shape	Hollow cylinders made of two protein chains twisted around each other	Protein fiber coils twisted into each other	Two actin chains twisted around one another
Main Functions	Organelle and vesicle movement; form mitotic spindles during cell reproduction; cell motility (in cilia and flagella)	Organize cell shape; positions organelles in cytoplasm structural support of the nuclear envelope and sarcomeres; involved in cell-to-cell and cell-to-matrix junctions	Keep cellular shape; allows movement of certain cells by forming cytoplasmatic extensions or contraction of actin fibers; involved in some cell-to-cell or cell-to-matrix junctions
Image	 Molecular structure of microtubules.	 Keratin intermediate filaments in skin cells (stained red).	 Actin cytoskeleton of mouse embryo cells.

External Structures

Flagella (flagellum, singular) are long, thin structures that stick out from the cell membrane. Both eukaryotic and prokaryotic cells can have flagella. Flagella help single-celled organisms move or swim towards food. The flagella of eukaryotic cells are normally used for movement too, such as in the movement of sperm cells. The flagella of either group are very different from each other. Prokaryotic flagella, shown below, are spiral-shaped and stiff. They spin around in a fixed base much like a screw does, which moves the cell in a tumbling fashion. Eukaryotic flagella are made of microtubules and bend and flex like a whip.



Bacterial flagella spin about in place, which causes the bacterial cell to "tumble."

Cilia (cilium, singular) are made up of extensions of the cell membrane that contain microtubules. Although both are used for movement, cilia are much shorter than flagella. Cilia cover the surface of some single-celled organisms, such as paramecium. Their cilia beat together to move the little animals through the water. In multicellular animals, including humans, cilia are usually found in large numbers on a single surface of cells. Multicellular animals' cilia usually move materials inside the body. For example, the mucociliary escalator of the respiratory system is made up of mucus-secreting cells that line the trachea and bronchi. Ciliated cells, shown in **Figure** 3.17, move mucus away from the lungs. Spores, bacteria, and debris are caught in the mucus which is moved to the esophagus by the ciliated cells, where it is swallowed.

The Nucleus and Other Organelles

The nucleus is a membrane-enclosed organelle found in most eukaryotic cells. The nucleus is the largest organelle in the cell and contains most of the cell's genetic information (mitochondria also contain DNA, called mitochondrial DNA, but it makes up just a small percentage of the cell's overall DNA content). The genetic information, which contains the information for the structure and function of the organism, is found encoded in DNA in the form of genes. A **gene** is a short segment of DNA that contains information to encode an RNA molecule or a protein strand. DNA in the nucleus is organized in long linear strands that are attached to different proteins. These proteins help the DNA to coil up for better storage

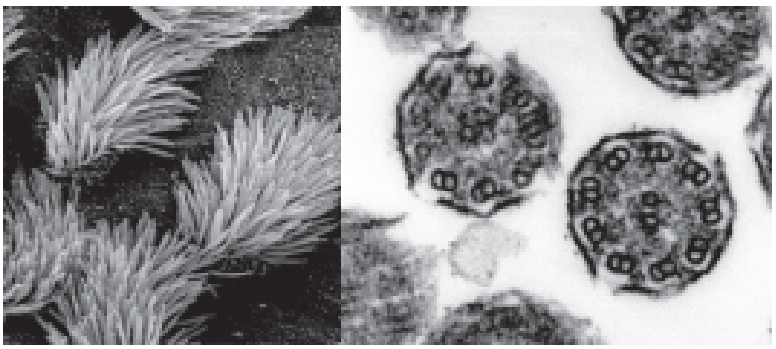


Figure 3.17: Left: Scanning electron micrograph (SEM), of the cilia sticking up from human lung cells. Right: Electron micrograph of cross-section of two cilia (not human), showing the positions of the microtubules inside. Note how there are nine groups of two microtubules (called dimers) in each cilium. Each dimer is made up of an alpha and a beta tubulin protein that are connected together.

in the nucleus. Think how a string gets tightly coiled up if you twist one end while holding the other end. These long strands of coiled-up DNA and proteins are called **chromosomes.** Each chromosome contains many genes. The function of the nucleus is to maintain the integrity of these genes and to control the activities of the cell by regulating gene expression. **Gene expression** is the process by which the information in a gene is "decoded" by various cell molecules to produce a functional gene product, such as a protein molecule or an RNA molecule.

The degree of DNA coiling determines whether the chromosome strands are short and thick or long and thin. Between cell divisions, the DNA in chromosomes is more loosely coiled and forms long thin strands called chromatin. Before the cell divides, the chromatin coil up more tightly and form chromosomes. Only chromosomes stain clearly enough to be seen under a microscope. The word chromosome comes from the Greek word chroma, (color) and soma, (body) due to its ability to be stained strongly by dyes.

Nuclear Envelope

The **nuclear envelope** is a double membrane of the nucleus that encloses the genetic material. It separates the contents of the nucleus from the cytoplasm. The nuclear envelope is made of two lipid bilayers, an inner membrane and an outer membrane. The outer membrane is continuous with the rough endoplasmic reticulum. Many tiny holes called nuclear pores are found in the nuclear envelope. These nuclear pores help to regulate the exchange of materials (such as RNA and proteins) between the nucleus and the cytoplasm.

Nucleolus

The nucleus of many cells also contains an organelle called a **nucleolus**, shown in **Figure** 3.18. The nucleolus is mainly involved in the assembly of ribosomes. **Ribosomes** are organelles made of protein and ribosomal RNA (rRNA), and they build cellular proteins in the cytoplasm. The function of the rRNA is to provide a way of decoding the genetic messages within another type of RNA called mRNA, into amino acids. After being made in the nucleolus, ribosomes are exported to the cytoplasm where they direct protein synthesis.

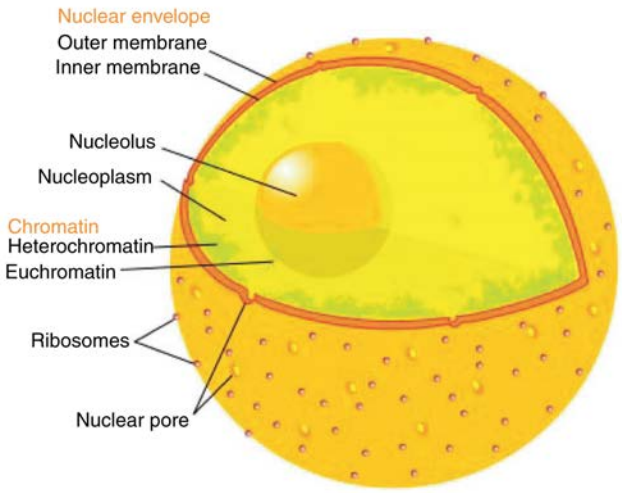


Figure 3.18: The eukaryotic cell nucleus. Visible in this diagram are the ribosome-studded double membranes of the nuclear envelope, the DNA (as chromatin), and the nucleolus. Within the cell nucleus is a viscous liquid called nucleoplasm, similar to the cytoplasm found outside the nucleus. The chromatin (which is normally invisible), is visible in this figure only to show that it is spread out throughout the nucleus.

Centrioles

Centrioles are rod-like structures made of short microtubules. Nine groups of three microtubules make up each centriole. Two perpendicularly placed centrioles make up the centrosome. Centrioles are very important in cellular division, where they arrange the mitotic spindles that pull the chromosome apart during mitosis.

Mitochondria

A **mitochondrion** (mitochondria, plural), is a membrane-enclosed organelle that is found in most eukaryotic cells. Mitochondria are called the "power plants" of the cell because they use energy from organic compounds to make ATP. ATP is the cell's energy source that is used for such things such as movement and cell division. Some ATP is made in the cytosol of the cell, but most of it is made inside mitochondria. The number of mitochondria in a cell depends on the cell's energy needs. For example, active human muscle cells may have thousands of mitochondria, while less active red blood cells do not have any.

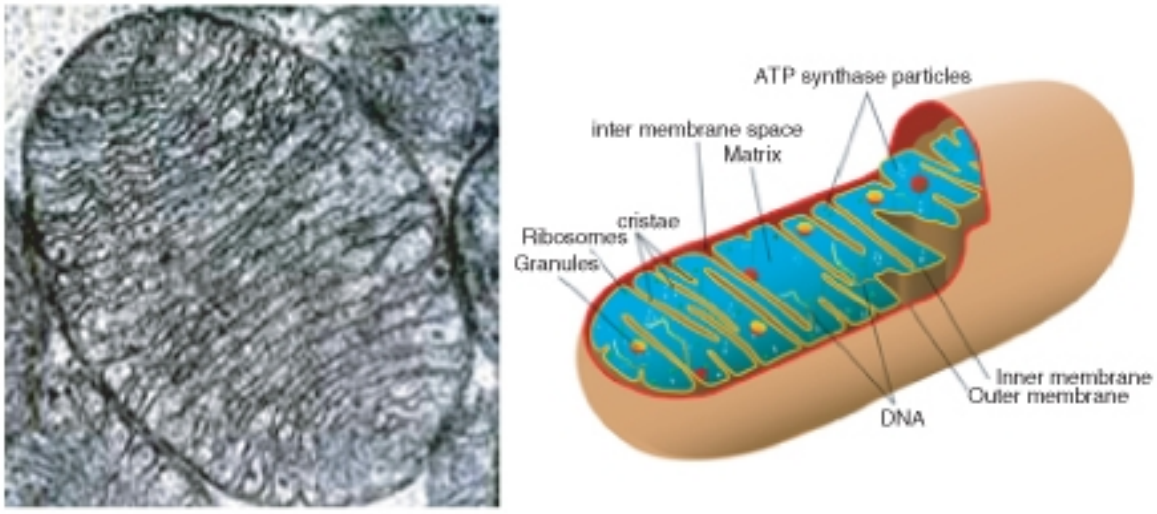


Figure 3.19: Electron micrograph of a single mitochondrion within which you can see many cristae. Mitochondria range from 1 to 10 m in size. This model of a mitochondrian shows the organized arrangement of the inner and outer membranes, the protein matrix, and the folded inner mitochondrial membranes.

As **Figure** 3.19 **(a) and (b)** shows, a mitochondrion has two phospholipids membranes. The smooth outer membrane separates the mitochondrion from the cytosol. The inner membrane has many folds, called cristae. The fluid-filled inside of the mitochondrian, called matrix, is where most of the cell's ATP is made.

Although most of a cell's DNA is contained in the cell nucleus, mitochondria have their own DNA. Mitochandria are able to reproduce asexually and scientists think that they are descended from prokaryotes. According to the endosymbiotic theory, mitochondria were once free-living prokaryotes that infected ancient eukaryotic cells. The invading prokaryotes were protected inside the eukaryotic host cell, and in turn the prokaryote supplied extra ATP to its host.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** (plural, reticuli) is a network of phospholipid membranes that form hollow tubes, flattened sheets, and round sacs. These flattened, hollow folds and sacs are called cisternae. The ER has two major functions:

- **Transport**: Molecules, such as proteins, can move from place to place inside the ER, much like on an intracellular highway.
- **Synthesis**: Ribosomes that are attached to ER, similar to unattached ribosomes, make proteins. Lipids are also produced in the ER.

There are two types of endoplasmic reticulum, rough endoplasmic reticulum (RER) and smooth endoplasmic reticulum (SER).

- **Rough endoplasmic reticulum** is studded with ribosomes which gives it a "rough" appearance. These ribosomes make proteins that are then transported from the ER in small sacs called transport vesicles. The transport vesicles pinch off the ends of the ER. The rough endoplasmic reticulum works with the Golgi apparatus to move new proteins to their proper destinations in the cell. The membrane of the RER is continuous with the outer layer of the nuclear envelope.
- **Smooth endoplasmic reticulum** does not have any ribosomes attached to it, and so it has a smooth appearance. SER has many different functions some of which are: lipid synthesis, calcium ion storage, and drug detoxification. Smooth endoplasmic reticulum is found in both animal and plant cells and it serves different functions in each. The SER is made up of tubules and vesicles that branch out to form a network. In some cells there are dilated areas like the sacs of RER. Smooth endoplasmic reticulum and RER form an interconnected network.

Ribosomes

Ribosomes are small organelles and are the site of protein synthesis (or assembly). They are made of ribosomal protein and ribosomal RNA. Each ribosome has two parts, a large and a small subunit, as shown in **Figure** 3.21. The subunits are attached to each other. Ribosomes can be found alone or in groups within the cytoplasm. Some ribosomes are attached to the endoplasmic reticulum (as shown in **Figure** 3.20), and others are attached to the nuclear envelope.

Ribozymes are RNA molecules that catalyzes chemical reactions, such as translation. Translation is the process of ordering the amino acids in the assembly of a protein, and more will be discussed on translation in a later chapter. Briefly, the ribosomes interact with other RNA molecules to make chains of amino acids called polypeptide chains, due to the peptide

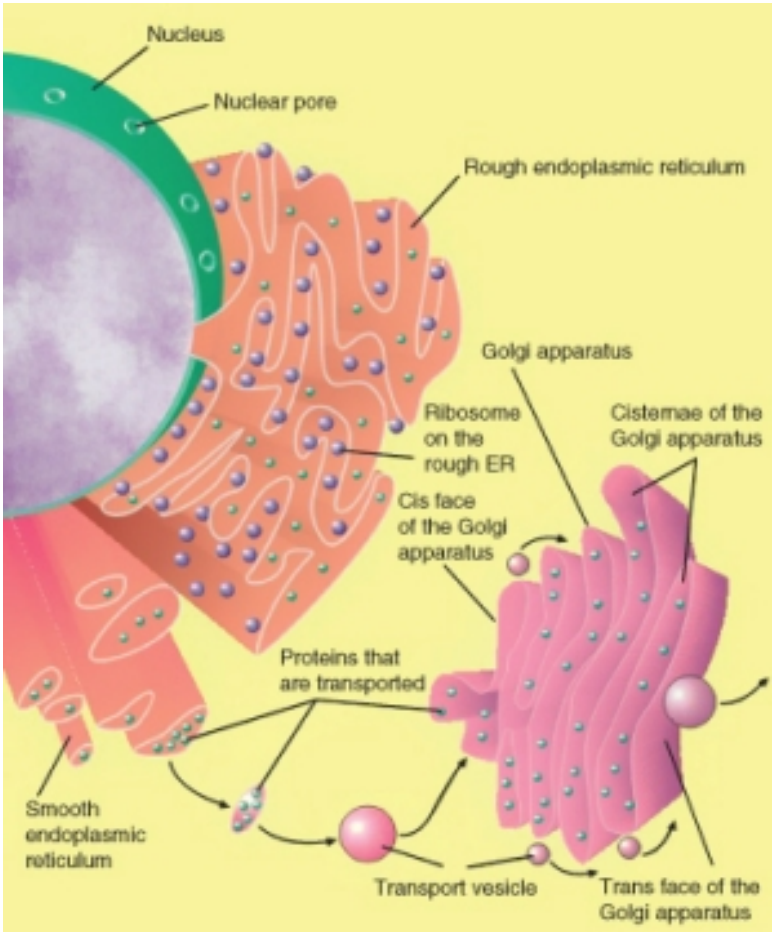


Figure 3.20: Image of nucleus, endoplasmic reticulum and Golgi apparatus, and how they work together. The process of secretion from endoplasmic reticuli (orange) to Golgi apparatus (pink) is shown.

bond that forms between individual amino acids. Polypeptide chains are built from the genetic instructions held within a messenger RNA molecule. Polypeptide chains that are made on the rough ER are inserted directly into the ER and then are transported to their various cellular destinations. Ribosomes on the rough ER usually produce proteins that are destined for the cell membrane.

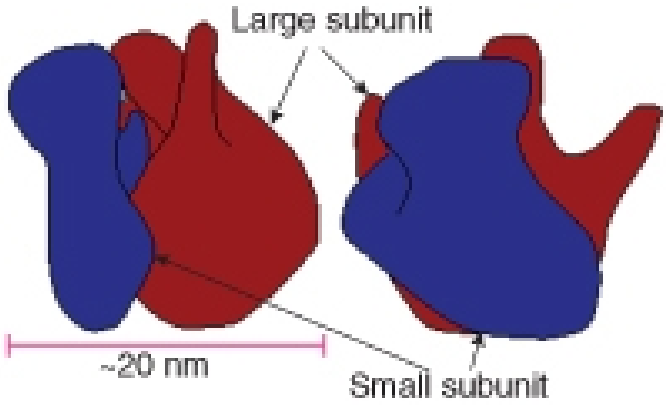


Figure 3.21: The two subunits that make up a ribosome, small organelles that are intercellular protein factories.

Golgi Apparatus

The **Golgi apparatus** is a large organelle that is usually made up of five to eight cup-shaped, membrane-covered discs called cisternae, as shown in **Figure** 3.20. The cisternae look a bit like a stack of deflated balloons. The Golgi apparatus modifies, sorts, and packages different substances for secretion out of the cell, or for use within the cell. The Golgi apparatus is found close to the nucleus of the cell where it modifies proteins that have been delivered in transport vesicles from the RER. It is also involved in the transport of lipids around the cell. Pieces of the Golgi membrane pinch off to form vesicles that transport molecules around the cell. The Golgi apparatus can be thought of as similar to a post office; it packages and labels "items" and then sends them to different parts of the cell. Both plant and animal cells have a Golgi apparatus. Plant cells can have up to several hundred Golgi stacks scattered throughout the cytoplasm. In plants, the Golgi apparatus contains enzymes that synthesize some of the cell wall polysaccharides.

Vesicles

A **vesicle** is a small, spherical compartment that is separated from the cytosol by at least one lipid bilayer. Many vesicles are made in the Golgi apparatus and the endoplasmic reticulum, or are made from parts of the cell membrane. Vesicles from the Golgi apparatus can be seen in **Figure** 3.20. Because it is separated from the cytosol, the space inside the vesicle can be made to be chemically different from the cytosol. Vesicles are basic tools of the cell for organizing metabolism, transport, and storage of molecules. Vesicles are also used as chemical reaction chambers. They can be classified by their contents and function.

- **Transport vesicles** are able to move molecules between locations inside the cell. For example, transport vesicles move proteins from the rough endoplasmic reticulum to the Golgi apparatus.
- **Lysosomes** are vesicles that are formed by the Golgi apparatus. They contain powerful enzymes that could break down (digest) the cell. Lysosomes break down harmful cell products, waste materials, and cellular debris and then force them out of the cell. They also digest invading organisms such as bacteria. Lysosomes also break down cells that are ready to die, a process called autolysis.
- **Peroxisomes** are vesicles that use oxygen to break down toxic substances in the cell. Unlike lysosomes, which are formed by the Golgi apparatus, peroxisomes self replicate by growing bigger and then dividing. They are common in liver and kidney cells that break down harmful substances. Peroxisomes are named for the hydrogen peroxide (H_2O_2) that is produced when they break down organic compounds. Hydrogen peroxide is toxic, and in turn is broken down into water (H_2O) and oxygen (O_2) molecules.

Vacuoles

Vacuoles are membrane-bound organelles that can have secretory, excretory, and storage functions. Many organisms will use vacuoles as storage areas and some plant cells have very large vacuoles. Vesicles are much smaller than vacuoles and function in transporting materials both within and to the outside of the cell.

Special Structures in Plant Cells

Most of the organelles that have been discussed are common to both animal and plant cells. However, plant cells also have features that animal cells do not have; they have a cell wall, a large central vacuole, and plastids such as chloroplasts.

Plants have very different lifestyles from animals, and these differences are apparent when you examine the structure of the plant cell. Plants make their own food in a process called photosynthesis. They take in carbon dioxide (CO_2) and water (H_2O) and convert them into sugars. The features unique to plant cells can be seen in **Figure** 3.22.

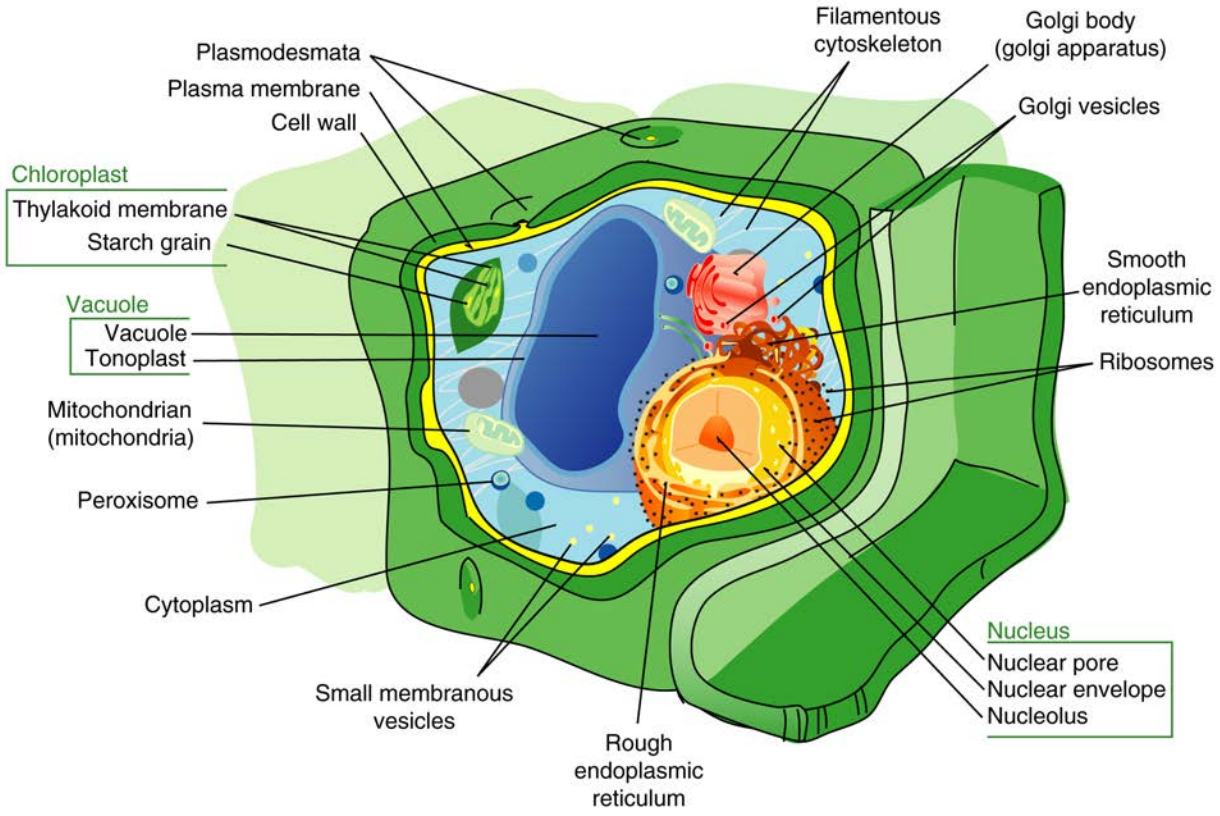


Figure 3.22: In addition to containing most of the organelles found in animal cells, plant cells also have a cell wall, a large central vacuole, and plastids. These three features are not found in animal cells.

Cell Wall

A cell wall is a rigid layer that is found outside the cell membrane and surrounds the cell. The cell wall contains not only cellulose and protein, but other polysaccharides as well. In fact, two other classes of polysaccharides, hemicelluloses and pectic polysaccharides, can comprise 30% of the dry mass of the cell wall. The cell wall provides structural support and protection. Pores in the cell wall allow water and nutrients to move into and out of the cell. The cell wall also prevents the plant cell from bursting when water enters the cell.

Microtubules guide the formation of the plant cell wall. Cellulose is laid down by enzymes to form the primary cell wall. Some plants also have a secondary cell wall. The secondary wall contains a lignin, a secondary cell component in plant cells that have completed cell growth/expansion.

Central Vacuole

Most mature plant cells have a **central vacuole** that occupies more than 30% of the cell's volume, but can also occupy as much as 90% of the volume of certain cells. The central vacuole is surrounded by a membrane called the tonoplast. The central vacuole has many functions. Aside from storage, the main role of the vacuole is to maintain turgor pressure against the cell wall. Proteins found in the tonoplast control the flow of water into and out of the vacuole. The central vacuole also stores the pigments that color flowers.

The central vacuole contains large amounts of a liquid called cell sap, which differs in composition to the cell cytosol. Cell sap is a mixture of water, enzymes, ions, salts, and other substances. Cell sap may also contain toxic byproducts that have been removed from the cytosol. Toxins in the vacuole may help to protect some plants from being eaten.

Plastids

Plant plastids are a group of closely related membrane-bound organelles that carry out many functions. They are responsible for photosynthesis, for storage of products such as starch, and for the synthesis of many types of molecules that are needed as cellular building blocks. Plastids have the ability to change their function between these and other forms. Plastids contain their own DNA and some ribosomes, and scientists think that plastids are descended from photosynthetic bacteria that allowed the first eukaryotes to make oxygen. The main types of plastids and their functions are:

- **Chloroplasts** are the organelle of photosynthesis. They capture light energy from the sun and use it with water and carbon dioxide to make food (sugar) for the plant. The arrangement of chloroplasts in a plant's cells can be seen in **Figure** 3.23.
- **Chromoplasts** make and store pigments that give petals and fruit their orange and yellow colors.

- **Leucoplasts** do not contain pigments and are located in roots and non-photosynthetic tissues of plants. They may become specialized for bulk storage of starch, lipid, or protein. However, in many cells, leucoplasts do not have a major storage function; instead they make molecules such as fatty acids and many amino acids.

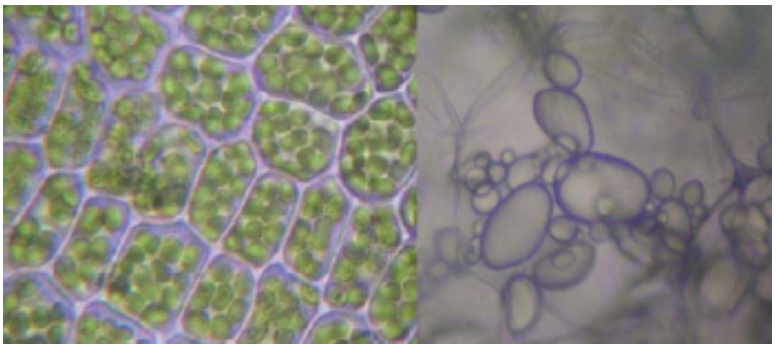


Figure 3.23: Plant cells with visible chloroplasts (left). Starch-storing potato leucoplasts (right).

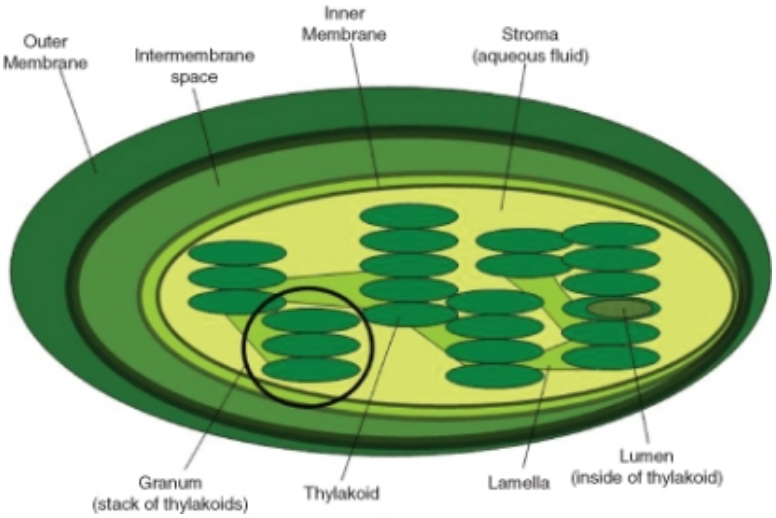


Figure 3.24: The internal structure of a chloroplast, with a granal stack of thylakoids circled.

Chloroplasts capture light energy from the sun and use it with water and carbon dioxide to produce sugars for food. Chloroplasts look like flat discs that are usually 2 to 10 micrometers in diameter and 1 micrometer thick. A model of a chloroplast is shown in **Figure** 3.24. The chloroplast is enclosed by an inner and an outer phospholipid membrane. Between these two layers is the intermembrane space. The fluid within the chloroplast is called the **stroma**, and it contains one or more molecules of small circular DNA. The stroma also has ribosomes. Within the stroma are stacks of **thylakoids**, the sub-organelles which are the site

of photosynthesis. The thylakoids are arranged in stacks called **grana** (singular: granum). A thylakoid has a flattened disk shape. Inside it is an empty area called the thylakoid space or lumen. Photosynthesis takes place on the thylakoid membrane.

Within the thylakoid membrane is the complex of proteins and light-absorbing pigments, such as chlorophyll and carotenoids. This complex allows capture of light energy from many wavelengths because chlorophyll and carotenoids both absorb different wavelengths of light. You will learn more about how chloroplasts convert light energy into chemical energy in the Photosynthesis chapter.

Organization of Cells

Biological organization exists at all levels in organisms. It can be seen at the smallest level, in the molecules that made up such things as DNA and proteins, to the largest level, in an organism such as a blue whale, the largest mammal on Earth. Similarly, single celled prokaryotes and eukaryotes show order in the way their cells are arranged. Single-celled organisms such as an amoeba are free-floating and independent-living. Their single-celled "bodies" are able to carry out all the processes of life such as metabolism and respiration without help from other cells. Some single-celled organisms such as bacteria can group together and form a biofilm. A **biofilm** is a large grouping of many bacteria that sticks to a surface and makes a protective coating over itself. Biofilms can show similarities to multicellular organisms. Division of labor is the process in which one group of cells does one job (such as making the "glue" that sticks the biofilm to the surface) while another group of cells does another job (such as taking in nutrients). Multicellular organisms carry out their life processes through division of labor and they have specialized cells that do specific jobs. However, biofilms are not considered a multicellular organism and are instead called colonial organisms. The difference between a multicellular organism and a colonial organism is that individual organisms from a colony or biofilm can, if separated, survive on their own, while cells from a multicellular organism (e.g., liver cells) cannot.

Colonial Organisms

Colonial organisms were probably one of the first evolutionary steps towards multicellular organisms. Algae of the genus *Volvox* are an example of the border between colonial organisms and multicellular organisms.

Each *Volvox*, shown in **Figure** 3.25, is a colonial organism. It is made up of between 1000 to 3000 photosynthetic algae that are grouped together into a hollow sphere. The sphere has a distinct front and back end. The cells have eyespots, which are more developed in the cells near the front. This enables the colony to swim towards light.

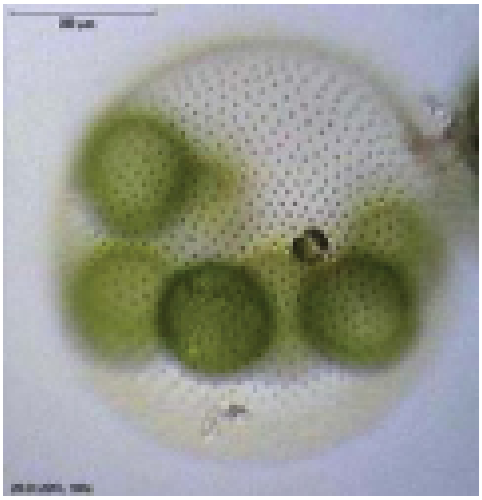


Figure 3.25: Colonial algae of the genus .

Origin of Multicellularity

The oldest known multicellular organism is a red algae *Bangiomorpha pubescens*, fossils of which were found in 1.2 billion year old rock. However, the first organisms were single celled. How multicellular organisms developed is the subject of much debate.

Scientists think that multicellularity arose from cooperation between many organisms of the same species. The **Colonial Theory** proposes that this cooperation led to the development of a multicellular organism. Many examples of cooperation between organisms in nature have been observed. For example, a certain species of amoeba (a single-celled animal) groups together during times of food shortage and forms a colony that moves as one to a new location. Some of these amoebas then become slightly differentiated from each other. *Volvox,* shown in **Figure** 3.25, is another example of a colonial organism. Most scientists accept that the Colonial theory explains how multicellular organisms evolved.

Multicellular organisms are organisms that are made up of more than one type of cell and have specialized cells that are grouped together to carry out specialized functions. Most life that you can see without a microscope is multicellular. As discussed earlier, the cells of a multicellular organism would not survive as independent cells. The body of a multicellular organism, such as a tree or a cat, exhibits organization at several levels: tissues, organs, and organ systems. Similar cells are grouped into tissues, groups of tissues make up organs, and organs with a similar function are grouped into an organ system.

Levels of Organization in Multicellular Organisms

The simplest living multicellular organisms, sponges, are made of many specialized types of cells that work together for a common goal. Such cell types include digestive cells, tubular

pore cells; and epidermal cells. Though the different cell types create a large organized, multicellular structure—the visible sponge—they are not organized into true interconnected tissues. If a sponge is broken up by passing it through a sieve, the sponge will reform on the other side. However, if the sponge's cells are separated from each other, the individual cell types cannot survive alone. Simpler colonial organisms, such as members of the genus *Volvox,* as shown in **Figure** 3.25, differ in that their individual cells are free-living and can survive on their own if separated from the colony.

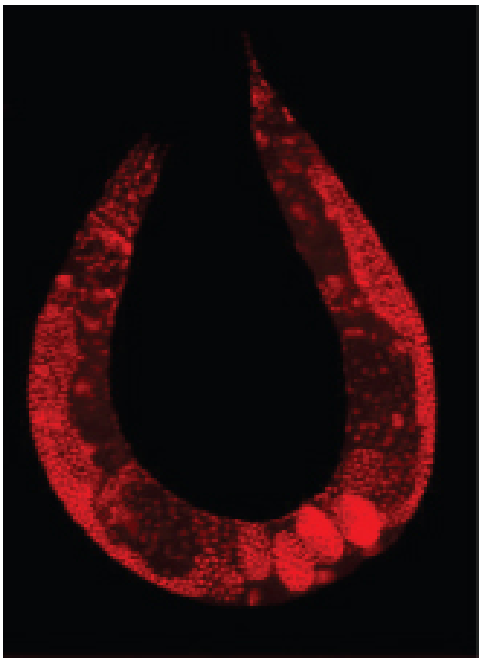


Figure 3.26: This roundworm, a multicellular organism, was stained to highlight the nuclei of all the cells in its body (red dots).

A **tissue** is a group of connected cells that have a similar function within an organism. More complex organisms such as jellyfish, coral, and sea anemones have a tissue level of organization. For example, jellyfish have tissues that have separate protective, digestive, and sensory functions.

Even more complex organisms, such as the roundworm shown in **Figure** 3.26, while also having differentiated cells and tissues, have an organ level of development. An **organ** is a group of tissues that has a specific function or group of functions. Organs can be as primitive as the brain of a flatworm (a group of nerve cells), as large as the stem of a sequoia (up to 90 meters, or 300 feet, in height), or as complex as a human liver.

The most complex organisms (such as mammals, trees, and flowers) have organ systems. An **organ system** is a group of organs that act together to carry out complex related functions, with each organ focusing on a part of the task. An example is the human digestive system in which the mouth ingests food, the stomach crushes and liquifies it, the pancreas and gall

bladder make and release digestive enzymes, and the intestines absorb nutrients into the blood.

Lesson Summary

- The plasma membrane is a selectively permeable lipid bilayer that contains mostly lipids and proteins. These lipids and proteins are involved in many cellular processes.
- The gel-like material within the cell that holds the organelles is called cytoplasm. The cytosol, which is the watery substance that does not contain organelles, is made up of 80% to 90% water.
- The cytoskeleton has many functions. It helps to maintain cell shape, it holds organelles in place, and for some cells, it enables cell movement. The cytoskeleton also plays important roles in both the intracellular movement of substances and in cell division. Three main kinds of cytoskeleton fibers are microtubules, intermediate filaments, and microfilaments.
- Cilia are extensions of the cell membrane that contain microtubules. Although both are used for movement, cilia are much shorter than flagella. Cilia cover the surface of some single-celled animals, such as paramecium, but cover only one side of cells in some multicellular organisms.
- There are three features that plant cells have that animal cells do not have: a cell wall, a large central vacuole, and plastids.
- Mitochondria use energy from organic compounds to make ATP.
- Ribosomes are exported from the nucleolus, where they are made, to the cytoplasm.
- The Golgi apparatus is a large organelle that is usually made up of five to eight cup-shaped, membrane-covered discs called *cisternae*. It modifies, sorts, and packages different substances for secretion out of the cell, or for use within the cell.
- Individual organisms from a colonial organism or biofilm can, if separated, survive on their own, while cells from a multicellular organism (e.g., liver cells) cannot.
- A tissue is a group of connected cells that have a similar function within an organism. An organ is a group of tissues that has a specific function or group of functions, and an organ system is a group of organs that act together to perform complex related functions, with each organ focusing on a part of the task.

Summary Animations

- The following web site is an interactive representation of a plant and animal cell, with their various organelles.

http://www.cellsalive.com/cells/cell_model.htm

- The following animation is a detailed example of the functions of the specific parts of the cell.

http://www.johnkyrk.com/er.html

- The following site is a virtual cell where various organelles can be observed.

http://www.ibiblio.org/virtualcell/tour/cell/cell.htm

- Department of Biological Sciences, Carnegie Mellon University

http://telstar.ote.cmu.edu/biology/

Review Questions

1. What are the main components of a plasma membrane?
2. What does the fluid mosaic model describe?
3. What is the difference between cytoplasm and cytosol?
4. What type of molecule is common to all three parts of the cytoskeleton?
5. Name the three main parts of the cytoskeleton.
6. What structures do plant cells have that animal cells do not have?
7. Identify two functions of plastids in plant cells.
8. What is the main difference between rough endoplasmic reticulum and smooth endoplasmic reticulum?
9. List five organelles eukaryotes have that prokaryotes do not have.
10. What is a cell feature that distinguishes a colonial organism from a multicellular organism?
11. What is the difference between a cell and a tissue?
12. Identify two functions of the nucleus.
13. Identify the reason why mitochondria are called "power plants" of the cell.
14. If muscle cells become more active than they usually are, they will grow more mitochondria. Explain why this happens.

Further Reading / Supplemental Links

- N. J. Butterfield (2000). Bangiomorpha pubescens n. gen., n. sp.: implications for the evolution of sex, multicellularity, and the Mesoproterozoic/Neoproterozoic radiation of eukaryotes. *Paleobiology* 26 (3): 386–404.
- The Bacterial Cytoskeleton. Shih YL, Rothfield L. Microbiol Mol Biol Rev. 2006 Sep;70(3):729-54.
- http://www.ncbi.nlm.nih.gov/sites/entrez?cmd=Retrieve&db=pubmed&dopt=Abstract&list_uids=16959967
- http://en.wikipedia.org

Vocabulary

chloroplast The organelle of photosynthesis; captures light energy from the sun and uses it with water and carbon dioxide to make food (sugar) for the plant.

cilia (cilium) Made up of extensions of the cell membrane that contain microtubules; involved in movement.

cell wall A rigid layer that is found outside the cell membrane and surrounds the cell; provides structural support and protection.

cytoplasm The gel-like material within the cell that holds the organelles.

cytoskeleton A cellular "scaffolding" or "skeleton" that crisscrosses the cytoplasm; helps to maintain cell shape, it holds organelles in place, and for some cells, it enables cell movement.

endoplasmic reticulum (ER) A network of phospholipid membranes that form hollow tubes, flattened sheets, and round sacs; involved in transport of molecules, such as proteins, and the synthesis of proteins and lipids.

flagella (flagellum) Long, thin structures that stick out from the cell membrane; help single-celled organisms move or swim towards food.

Fluid Mosaic Model Model of the structure of cell membranes; proposes that integral membrane proteins are embedded in the phospholipid bilayer; some of these proteins extend all the way through the bilayer, and some only partially across it; also proposes that the membrane behaves like a fluid, rather than a solid.

gene A short segment of DNA that contains information to encode an RNA molecule or a protein strand.

gene expression The process by which the information in a gene is "decoded" by various cell molecules to produce a functional gene product, such as a protein molecule or an RNA molecule.

Golgi apparatus A large organelle that is usually made up of five to eight cup-shaped, membrane-covered discs called cisternae; modifies, sorts, and packages different substances for secretion out of the cell, or for use within the cell.

integral membrane proteins Proteins that are permanently embedded within the plasma membrane; involved in channeling or transporting molecules across the membrane or acting as cell receptors.

intermediate filaments Filaments that organize the inside structure of the cell by holding organelles and providing strength.

lipid bilayer A double layer of closely-packed lipid molecules; the cell membrane is a phospholipid bilayer.

lysosome A vesicle that contains powerful digestive enzymes.

membrane protein A protein molecule that is attached to, or associated with the membrane of a cell or an organelle.

microfilament Filament made of two thin actin chains that are twisted around one another; organizes cell shape; positions organelles in cytoplasm; involved in cell-to-cell and cell-to-matrix junctions.

microtubules Hollow cylinders that make up the thickest of the cytoskeleton structures; made of the protein tubulin, with two subunits, alpha and beta tubulin; involved in organelle and vesicle movement; form mitotic spindles during cell division; involved in cell motility (in cilia and flagella).

mitochondria (mitochondrion) Membrane-enclosed organelles that are found in most eukaryotic cells; called the "power plants" of the cell because they use energy from organic compounds to make ATP.

multicellular organisms Organisms that are made up of more than one type of cell; have specialized cells that are grouped together to carry out specialized functions.

nucleus The membrane-enclosed organelle found in most eukaryotic cells; contains the genetic material (DNA).

organ A group of tissues that has a specific function or group of functions.

organ system A group of organs that acts together to carry out complex related functions, with each organ focusing on a part of the task.

peripheral membrane proteins Proteins that are only temporarily associated with the membrane; can be easily removed, which allows them to be involved in cell signaling.

peroxisomes Vesicles that use oxygen to break down toxic substances in the cell.

phospholipid A lipid made up of up of a polar, phosphorus-containing head, and two long fatty acid, non-polar "tails." The head of the molecule is hydrophilic (water-loving), and the tail is hydrophobic (water-fearing).

plasma membrane Phospholipid bilayer that separates the internal environment of the cell from the outside environment.

ribosomes Organelles made of protein and ribosomal RNA (rRNA); where protein synthesis occurs.

selective permeability The ability to allow only certain molecules in or out of the cell; characteristic of the cell membrane; also called the cell membrane.

spontaneous generation The belief that living organisms grow directly from decaying organic substances.

tissue A group of connected cells that has a similar function within an organism.

transport vesicle A vesicle that is able to move molecules between locations inside the cell.

vacuole Membrane-bound organelles that can have secretory, excretory, and storage functions; plant cells have a large central vacuole.

vesicle A small, spherical compartment that is separated from the cytosol by at least one lipid bilayer.

Points to Consider

- How do you think small molecules, or even water, get through the cell membrane?
- Is it possible that proteins help in this transport process?
- What type of proteins would help with transport?

3.3 Lesson 3.3: Cell Transport and Homeostasis

Lesson Objectives

- Identify two ways that molecules and ions cross the plasma membrane.
- Distinguish between diffusion and osmosis.
- Identify the role of ion channels in facilitated diffusion.
- Compare passive and active transport.
- Identify the connection between vesicles and active transport.
- Compare endocytosis and exocytosis.
- Outline the process of cell communication.

Introduction

Probably the most important feature of a cell's phospholipid membranes is that they are selectively permeable. A membrane that is **selectively permeable** has control over what molecules or ions can enter or leave the cell, as shown in **Figure** 3.27. The permeability of a membrane is dependent on the organization and characteristics of the membrane lipids and proteins. In this way, cell membranes help maintain a state of homeostasis within cells (and tissues, organs, and organ systems) so that an organism can stay alive and healthy.

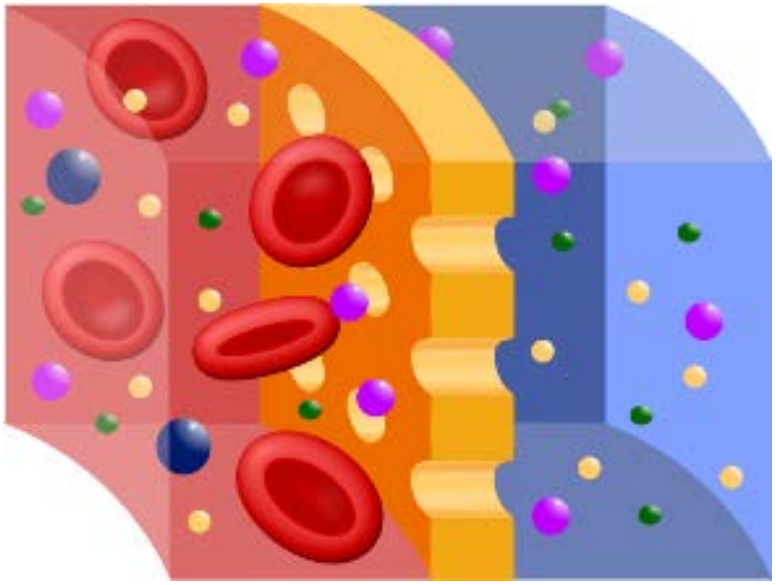


Figure 3.27: A selectively permeable membrane allows certain molecules through, but not others.

Transport Across Membranes

The molecular make-up of the phospholipid bilayer limits the types of molecules that can pass through it. For example, hydrophobic (water-hating) molecules, such as carbon dioxide (CO_2) and oxygen (O_2), can easily pass through the lipid bilayer, but ions such as calcium (Ca^{2+}) and polar molecules such as water (H_2O) cannot. The hydrophobic interior of the phospholipid does not allow ions or polar molecules through because they are hydrophilic, or water loving. In addition, large molecules such as sugars and proteins are too big to pass through the bilayer. Transport proteins within the membrane allow these molecules to cross the membrane into or out of the cell. This way, polar molecules avoid contact with the nonpolar interior of the membrane, and large molecules are moved through large pores.

Every cell is contained within a membrane punctuated with transport proteins that act as channels or pumps to let in or force out certain molecules. The purpose of the transport proteins is to protect the cell's internal environment and to keep its balance of salts, nutrients, and proteins within a range that keeps the cell and the organism alive.

There are three main ways that molecules can pass through a phospholipid membrane. The first way requires no energy input by the cell and is called passive transport. The second way requires that the cell uses energy to pull in or pump out certain molecules and ions and is called active transport. The third way is through vesicle transport, in which large molecules are moved across the membrane in bubble-like sacks that are made from pieces of the membrane.

Passive Transport

Passive transport is a way that small molecules or ions move across the cell membrane without input of energy by the cell. The three main kinds of passive transport are diffusion, osmosis, and facilitated diffusion.

Diffusion

Diffusion is the movement of molecules from an area of high concentration of the molecules to an area with a lower concentration. The difference in the concentrations of the molecules in the two areas is called the **concentration gradient**. Diffusion will continue until this gradient has been eliminated. Since diffusion moves materials from an area of higher concentration to the lower, it is described as moving solutes "down the concentration gradient." The end result of diffusion is an equal concentration, or **equilibrium**, of molecules on both sides of the membrane.

If a molecule can pass freely through a cell membrane, it will cross the membrane by diffusion (**Figure** 3.28).

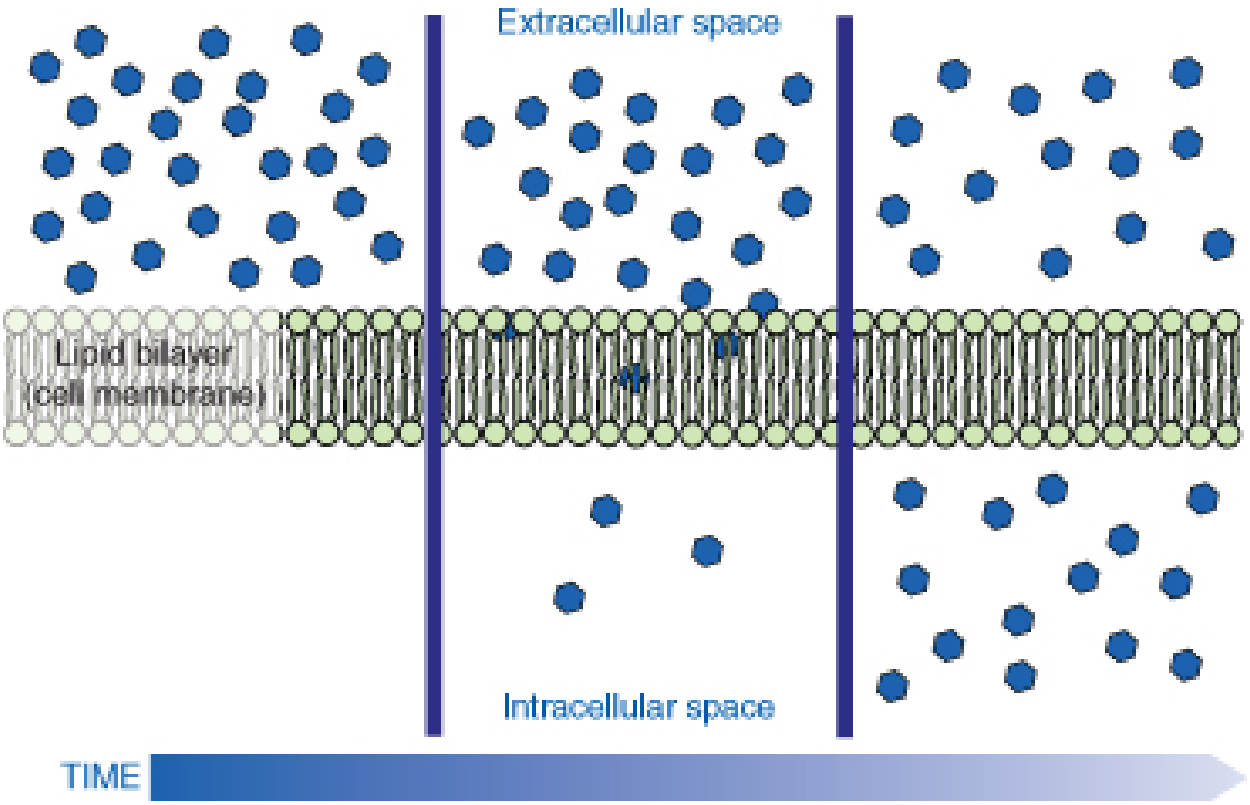


Figure 3.28: Molecules move from an area of high concentration to an area of lower concentration until an equilibrium is met. The molecules continue to cross the membrane at equilibrium, but at equal rates in both directions.

Osmosis

Imagine you have a cup that has 100ml water, and you add 15g of table sugar to the water. The sugar dissolves and the mixture that is now in the cup is made up of a solute (the sugar), that is dissolved in the solvent (the water). The mixture of a solute in a solvent is called a solution.

Imagine now that you have a second cup with 100ml of water, and you add 45 grams of table sugar to the water. Just like the first cup, the sugar is the solute, and the water is the solvent. But now you have two mixtures of different solute concentrations. In comparing two solutions of unequal solute concentration, the solution with the higher solute concentration is **hypertonic**, and the solution with the lower concentration is **hypotonic**. Solutions of equal solute concentration are **isotonic**. The first sugar solution is hypotonic to the second solution. The second sugar solution is hypertonic to the first.

You now add the two solutions to a beaker that has been divided by a selectively permeable membrane. The pores in the membrane are too small for the sugar molecules to pass through, but are big enough for the water molecules to pass through. The hypertonic solution is on one side of the membrane and the hypotonic solution on the other. The hypertonic solution has a lower water concentration than the hypotonic solution, so a concentration gradient of water now exists across the membrane. Water molecules will move from the side of higher water concentration to the side of lower concentration until both solutions are isotonic.

Osmosis is the diffusion of water molecules across a selectively permeable membrane from an area of higher concentration to an area of lower concentration. Water moves into and out of cells by osmosis. If a cell is in a hypertonic solution, the solution has a lower water concentration than the cell cytosol does, and water moves out of the cell until both solutions are isotonic. Cells placed in a hypotonic solution will take in water across their membrane until both the external solution and the cytosol are isotonic.

A cell that does not have a rigid cell wall (such as a red blood cell), will swell and lyse (burst) when placed in a hypotonic solution. Cells with a cell wall will swell when placed in a hypotonic solution, but once the cell is turgid (firm), the tough cell wall prevents any more water from entering the cell. When placed in a hypertonic solution, a cell without a cell wall will lose water to the environment, shrivel, and probably die. In a hypertonic solution, a cell with a cell wall will lose water too. The plasma membrane pulls away from the cell wall as it shrivels. The cell becomes plasmolyzed. Animal cells tend to do best in an isotonic environment, plant cells tend to do best in a hypotonic environment. This is demonstrated in **Figure** 3.29.

When water moves into a cell by osmosis, osmotic pressure may build up inside the cell. If a cell has a cell wall, the wall helps maintain the cell's water balance. Osmotic pressure is the main cause of support in many plants. When a plant cell is in a hypotonic environment, the osmotic entry of water raises the turgor pressure exerted against the cell wall until the pressure prevents more water from coming into the cell. At this point the plant cell is turgid.

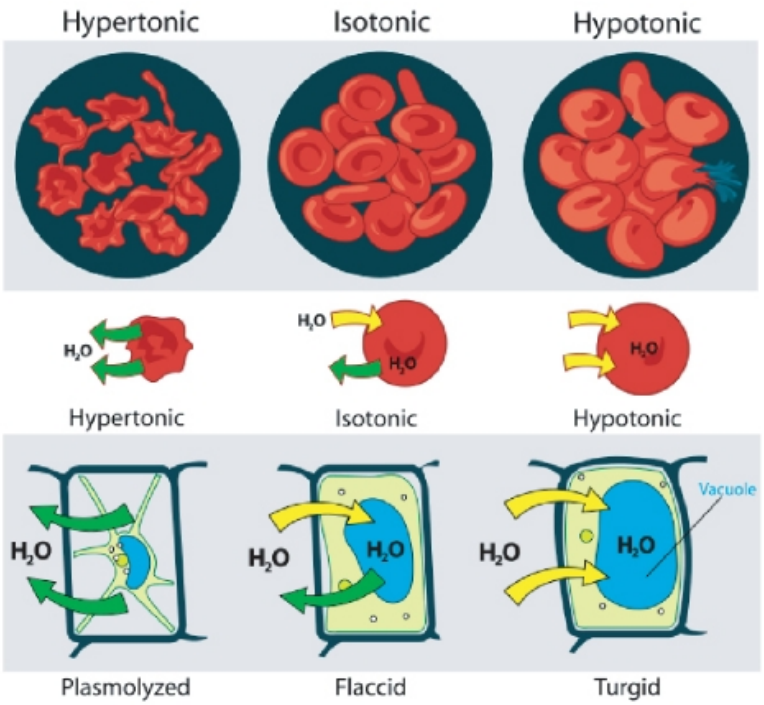


Figure 3.29: Unless an animal cell (such as the red blood cell in the top panel) has an adaptation that allows it to alter the osmotic uptake of water, it will lose too much water and shrivel up in a hypertonic environment. If placed in a hypotonic solution, water molecules will enter the cell causing it to swell and burst. Plant cells (bottom panel) become plasmolyzed in a hypertonic solution, but tend to do best in a hypotonic environment. Water is stored in the central vacuole of the plant cell.

The effects of osmotic pressures on plant cells are shown in **Figure** 3.30.

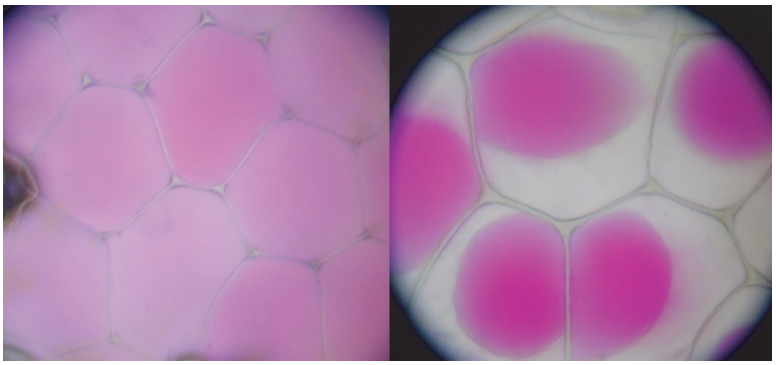


Figure 3.30: The central vacuoles of the plant cells in the left image are full of water, so the cells are turgid. The plant cells in the right image have been exposed to a hypertonic solution; water has left the central vacuole and the cells have become plasmolysed.

Osmosis can be seen very effectively when potato slices are added to a high concentration of salt solution (hypertonic). The water from inside the potato moves out of the potato cells to the salt solution, which causes the potato cells to lose turgor pressure. The more concentrated the salt solution, the greater the difference in the size and weight of the potato slice after plasmolysis.

The action of osmosis can be very harmful to organisms, especially ones without cell walls. For example, if a saltwater fish (whose cells are isotonic with seawater), is placed in fresh water, its cells will take on excess water, lyse, and the fish will die. Another example of a harmful osmotic effect is the use of table salt to kill slugs and snails.

Controlling Osmosis

Organisms that live in a hypotonic environment such as freshwater, need a way to prevent their cells from taking in too much water by osmosis. A **contractile vacuole** is a type of vacuole that removes excess water from a cell. Freshwater protists, such as the paramecia shown in **Figure** 3.31, have a contractile vacuole. The vacuole is surrounded by several canals, which absorb water by osmosis from the cytoplasm. After the canals fill with water, the water is pumped into the vacuole. When the vacuole is full, it pushes the water out of the cell through a pore. Other protists, such as members of the genus *Amoeba*, have contractile vacuoles that move to the surface of the cell when full and release the water into the environment.

Figure 3.31: The contractile vacuole is the star-like structure within the paramecia (at center-right)

Facilitated Diffusion

Facilitated diffusion is the diffusion of solutes through transport proteins in the plasma membrane. Facilitated diffusion is a type of passive transport. Even though facilitated diffusion involves transport proteins, it is still passive transport because the solute is moving down the concentration gradient.

As was mentioned earlier, small nonpolar molecules can easily diffuse across the cell membrane. However, due to the hydrophobic nature of the lipids that make up cell membranes, polar molecules (such as water) and ions cannot do so. Instead, they diffuse across the membrane through transport proteins. A **transport protein** completely spans the membrane, and allows certain molecules or ions to diffuse across the membrane. Channel proteins, gated channel proteins, and carrier proteins are three types of transport proteins that are involved in facilitated diffusion.

A **channel protein**, a type of transport protein, acts like a pore in the membrane that lets water molecules or small ions through quickly. Water channel proteins allow water to diffuse across the membrane at a very fast rate. Ion channel proteins allow ions to diffuse across the membrane.

A **gated channel protein** is a transport protein that opens a "gate," allowing a molecule to pass through the membrane. Gated channels have a binding site that is specific for a given molecule or ion. A stimulus causes the "gate" to open or shut. The stimulus may be chemical or electrical signals, temperature, or mechanical force, depending on the type of gated channel. For example, the sodium gated channels of a nerve cell are stimulated by a chemical signal which causes them to open and allow sodium ions into the cell. Glucose

molecules are too big to diffuse through the plasma membrane easily, so they are moved across the membrane through gated channels. In this way glucose diffuses very quickly across a cell membrane, which is important because many cells depend on glucose for energy.

A **carrier protein** is a transport protein that is specific for an ion, molecule, or group of substances. Carrier proteins "carry" the ion or molecule across the membrane by changing shape after the binding of the ion or molecule. Carrier proteins are involved in passive and active transport. A model of a channel protein and carrier proteins is shown in **Figure** 3.32.

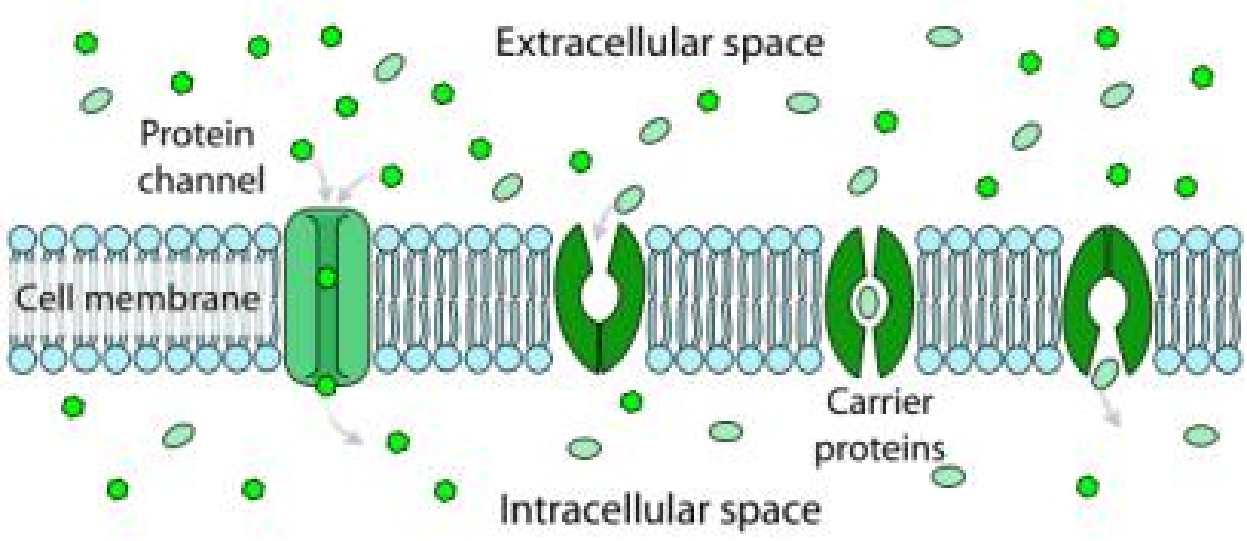


Figure 3.32: Facilitated diffusion in cell membrane. Channel proteins and carrier proteins are shown (but not a gated-channel protein). Water molecules and ions move through channel proteins. Other ions or molecules are also carried across the cell membrane by carrier proteins. The ion or molecule binds to the active site of a carrier protein. The carrier protein changes shape, and releases the ion or molecule on the other side of the membrane. The carrier protein then returns to its original shape.

Ion Channels

Ions such as sodium (Na^+), potassium (K^-), calcium (Ca^{2+}), and chloride (Cl^-), are important for many cell functions. Because they are polar, these ions do not diffuse through the membrane. Instead they move through ion channel proteins where they are protected from the hydrophobic interior of the membrane. **Ion channels** allow the formation of a concentration gradient between the extracellular fluid and the cytosol. Ion channels are very specific as they allow only certain ions through the cell membrane. Some ion channels are always open, others are "gated" and can be opened or closed. Gated ion channels can open or close in response to different types of stimuli such as electrical or chemical signals.

Active Transport

In contrast to facilitated diffusion which does not require energy and carries molecules or ions down a concentration gradient, active transport pumps molecules and ions against a concentration gradient. Sometimes an organism needs to transport something against a concentration gradient. The only way this can be done is through active transport which uses energy that is produced by respiration (ATP). In active transport, the particles move across a cell membrane from a lower concentration to a higher concentration. **Active transport** is the energy-requiring process of pumping molecules and ions across membranes "uphill" against a gradient.

- The active transport of small molecules or ions across a cell membrane is generally carried out by transport proteins that are found in the membrane.
- Larger molecules such as starch can also be actively transported across the cell membrane by processes called endocytosis and exocytosis (discussed later).

Sodium-Potassium Pump

Carrier proteins can work with a concentration gradient (passive transport), but some carrier proteins can move solutes against the concentration gradient (from high concentration to low), with energy input from ATP. As in other types of cellular activities, ATP supplies the energy for most active transport. One way ATP powers active transport is by transferring a phosphate group directly to a carrier protein. This may cause the carrier protein to change its shape, which moves the molecule or ion to the other side of the membrane. An example of this type of active transport system, as shown in **Figure** 3.33, is the **sodium-potassium pump,** which exchanges sodium ions for potassium ions across the plasma membrane of animal cells.

As is shown in **Figure** 3.33, three sodium ions bind with the protein pump inside the cell. The carrier protein then gets energy from ATP and changes shape. In doing so, it pumps the three sodium ions out of the cell. At that point, two potassium ions move in from outside the cell and bind to the protein pump. The sodium-potassium pump is found in the plasma membrane of almost every human cell and is common to all cellular life. It helps maintain cell potential and regulates cellular volume. Cystic fibrosis is a genetic disorder that results in a misshapen chloride ion pump. Chloride levels within the cells are not controlled properly, and the cells produce thick mucus. The chloride ion pump is important for creating sweat, digestive juices, and mucus.

The Electrochemical Gradient

The active transport of ions across the membrane causes an electrical gradient to build up across the plasma membrane. The number of positively charged ions outside the cell is

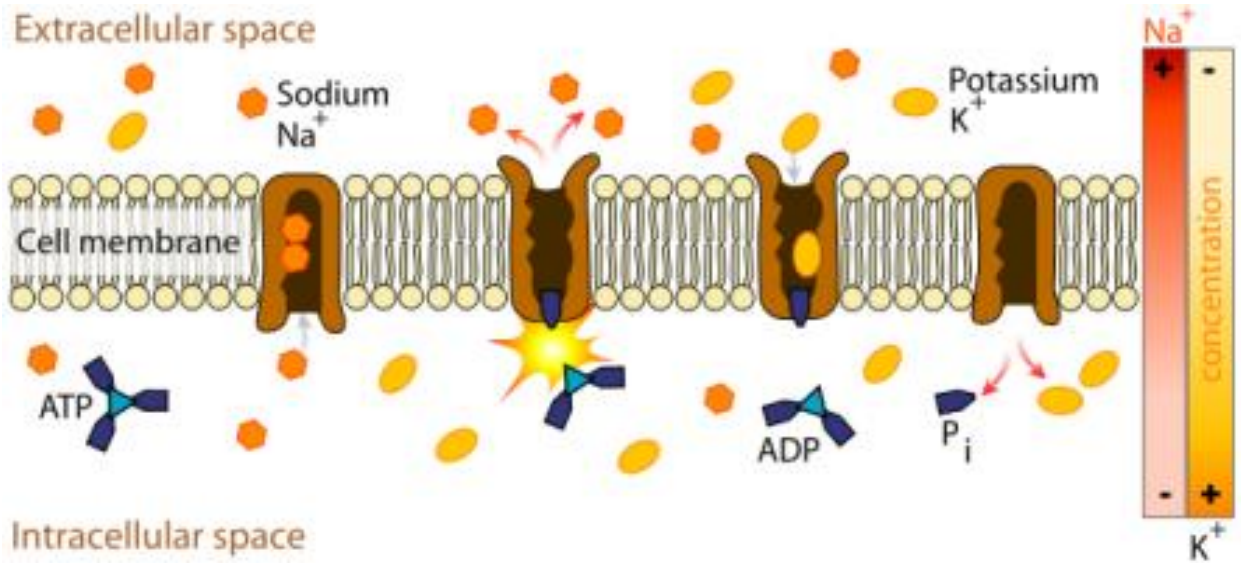


Figure 3.33: The sodium-potassium pump system moves sodium and potassium ions against large concentration gradients. It moves two potassium ions into the cell where potassium levels are high, and pumps three sodium ions out of the cell and into the extracellular fluid.

greater than the number of positively charged ions in the cytosol. This results in a relatively negative charge on the inside of the membrane, and a positive charge on the outside. This difference in charges causes a voltage across the membrane. Voltage is electrical potential energy that is caused by a separation of opposite charges, in this case across the membrane. The voltage across a membrane is called membrane potential. Membrane potential is very important for the conduction of electrical impulses along nerve cells.

Because the inside of the cell is negative compared to outside the cell, the membrane potential favors the movement of positively charged ions (cations) into the cell, and the movement of negative ions (anions) out of the cell. So, there are two forces that drive the diffusion of ions across the plasma membrane—a chemical force (the ions' concentration gradient), and an electrical force (the effect of the membrane potential on the ions' movement). These two forces working together are called an electrochemical gradient, and will be discussed in detail in the chapter Nervous and Endocrine Systems.

Vesicles and Active Transport

Some molecules or particles are just too large to pass through the plasma membrane or to move through a transport protein. So cells use two other methods to move these macromolecules (large molecules) into or out of the cell. Vesicles or other bodies in the cytoplasm move macromolecules or large particles across the plasma membrane. There are two types of vesicle transport, endocytosis and exocytosis.

Endocytosis and Exocytosis

Endocytosis is the process of capturing a substance or particle from outside the cell by engulfing it with the cell membrane. The membrane folds over the substance and it becomes completely enclosed by the membrane. At this point a membrane-bound sac, or vesicle pinches off and moves the substance into the cytosol. There are two main kinds of endocytosis:

- **Phagocytosis** or "cellular eating," occurs when the dissolved materials enter the cell. The plasma membrane engulfs the solid material, forming a phagocytic vesicle.
- **Pinocytosis** or "cellular drinking," occurs when the plasma membrane folds inward to form a channel allowing dissolved substances to enter the cell, as shown in **Figure** 3.34. When the channel is closed, the liquid is encircled within a pinocytic vesicle.

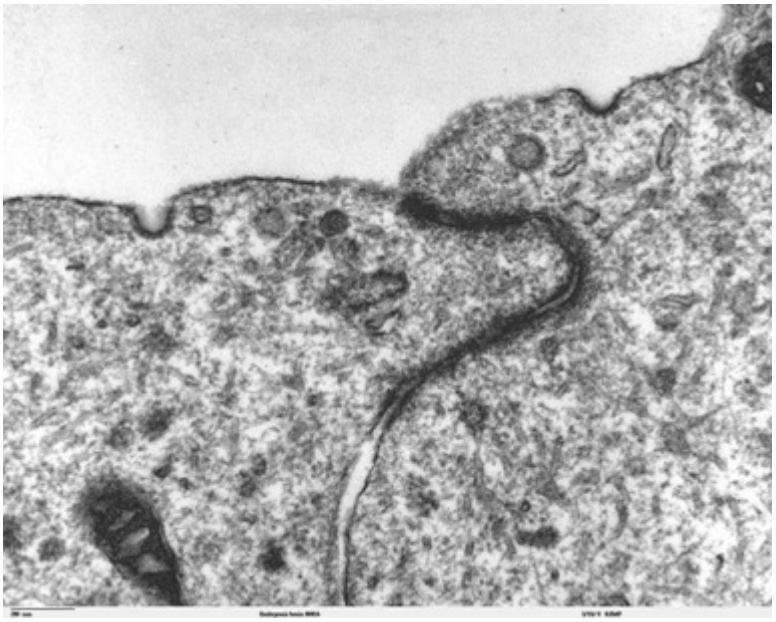


Figure 3.34: Transmission electron microscope image of brain tissue that shows pinocytotic vesicles. Pinocytosis is a type of endocytosis.

Exocytosis describes the process of vesicles fusing with the plasma membrane and releasing their contents to the outside of the cell, as shown in **Figure** 3.35. Exocytosis occurs when a cell produces substances for export, such as a protein, or when the cell is getting rid of a waste product or a toxin. Newly made membrane proteins and membrane lipids are moved on top the plasma membrane by exocytosis. For a detailed animation on cellular secretion, see http://vcell.ndsu.edu/animations/constitutivesecretion/first.htm.

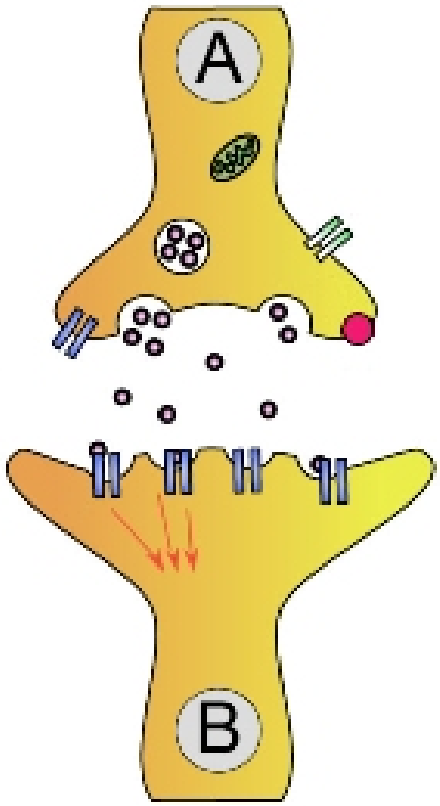


Figure 3.35: Mode of exocytosis at a synaptic junction, where two nerve cells meet. Chemical signal molecules are released from nerve cell A by exocytosis, and move toward receptors in nerve cell B. Exocytosis is an important part in cell signaling.

Homeostasis and Cell Function

Homeostasis refers to the balance, or equilibrium within the cell or a body. It is an organism's ability to keep a constant internal environment. Keeping a stable internal environment requires constant adjustments as conditions change inside and outside the cell. The adjusting of systems within a cell is called homeostatic regulation. Because the internal and external environments of a cell are constantly changing, adjustments must be made continuously to stay at or near the set point (the normal level or range). Homeostasis is a dynamic equilibrium rather than an unchanging state. The cellular processes discussed in this lesson all play an important role in homeostatic regulation. You will learn more about homeostasis in *The Human Body* chapter.

Cell Communication

To survive and grow, cells need to be able to "talk" with their cell neighbors and be able to detect change in their environment. Talking with neighbors is even more important to a cell if it is part of a multicellular organism. The billions of cells that make up your body need to be able to communicate with each other to allow your body to grow, and to keep you alive and healthy. The same is true for any organism. Cell signaling is a major area of research in biology today. Recently scientists have discovered that many different cell types, from bacteria to plants, use similar types of communication pathways, or cell-signaling mechanisms. This suggests that cell-signaling mechanisms evolved long before the first multicellular organism did.

The Language of Cells

For cells to be able to signal to each other, a few things are needed:

- a signal
- a cell receptor, which is usually on the plasma membrane, but can be found inside the cell
- a response to the signal

Cells that are communicating may be right next to each other or far apart. The type of chemical signal a cell will send differs depending on the distance the message needs to go. For example, hormones, ions, and neurotransmitters are all types of signals that are sent depending on the distance the message needs to go.

The target cell then needs to be able to recognize the signal. Chemical signals are received by the target cell on receptor proteins. As discussed earlier, most receptor proteins are found in the plasma membrane. Most receptors proteins are found on the plasma membrane, but

some are also found inside the cell. These receptor proteins are very specific for only one particular signal molecule, much like a lock that recognizes only one key. Therefore, a cell has lots of receptor proteins to recognize the large number of cell signal molecules. There are three stages to sending and receiving a cell "message:" reception, transduction, and response.

Signal Receptors

Cell-surface receptors are integral proteins—they reach right through the lipid bilayer, spanning from the outside to the inside of the cell. These receptor proteins are specific for just one kind of signal molecule. The signaling molecule acts as a ligand when it binds to a receptor protein. A **ligand** is a small molecule that binds to a larger molecule. Signal molecule binding causes the receptor protein to change its shape. At this point the receptor protein can interact with another molecule. The ligand (signal molecule) itself does not pass through the plasma membrane.

In eukaryotic cells, most of the intracellular proteins that are activated by a ligand binding to a receptor protein are enzymes. Receptor proteins are named after the type of enzyme that they interact with inside the cell. These enzymes include G proteins and protein kinases, likewise there are G-protein-linked receptors and tyrosine kinase receptors. A kinase is a protein involved in phosphorylation. A **G-protein linked receptor** is a receptor that works with the help of a protein called a G-protein. A G-protein gets its name from the molecule to which it is attached, guanosine triphosphate (GTP), or guanosine diphosphate (GDP). The GTP molecule is similar to ATP.

Once G proteins or protein kinase enzymes are activated by a receptor protein, they create molecules called second messengers. A **second messenger** is a small molecule that starts a change inside a cell in response to the binding of a specific signal to a receptor protein. Some second messenger molecules include small molecules called cyclic nucleotides, such as cyclic adenosine monophosphate (cAMP) and cyclic guanosine monophosphate (cGMP). Calcium ions (Ca^{2+}) also act as secondary messengers. Secondary messengers are a part of signal transduction pathways.

Signal Transduction

A **signal-transduction pathway** is the signaling mechanism by which a cell changes a signal on it surface into a specific response inside the cell. It most often involves an ordered sequence of chemical reactions inside the cell which is carried out by enzymes and other molecules. In many signal transduction processes, the number of proteins and other molecules participating in these events increases as the process progresses from the binding of the signal. A "signal cascade" begins. Think of a signal cascade as a chemical domino-effect inside the cell, in which one domino knocks over two dominos, which in turn knock over four dominos, and so on. The advantage of this type of signaling to the cell is that the message from one

little signal molecule can be greatly amplified and have a dramatic effect.

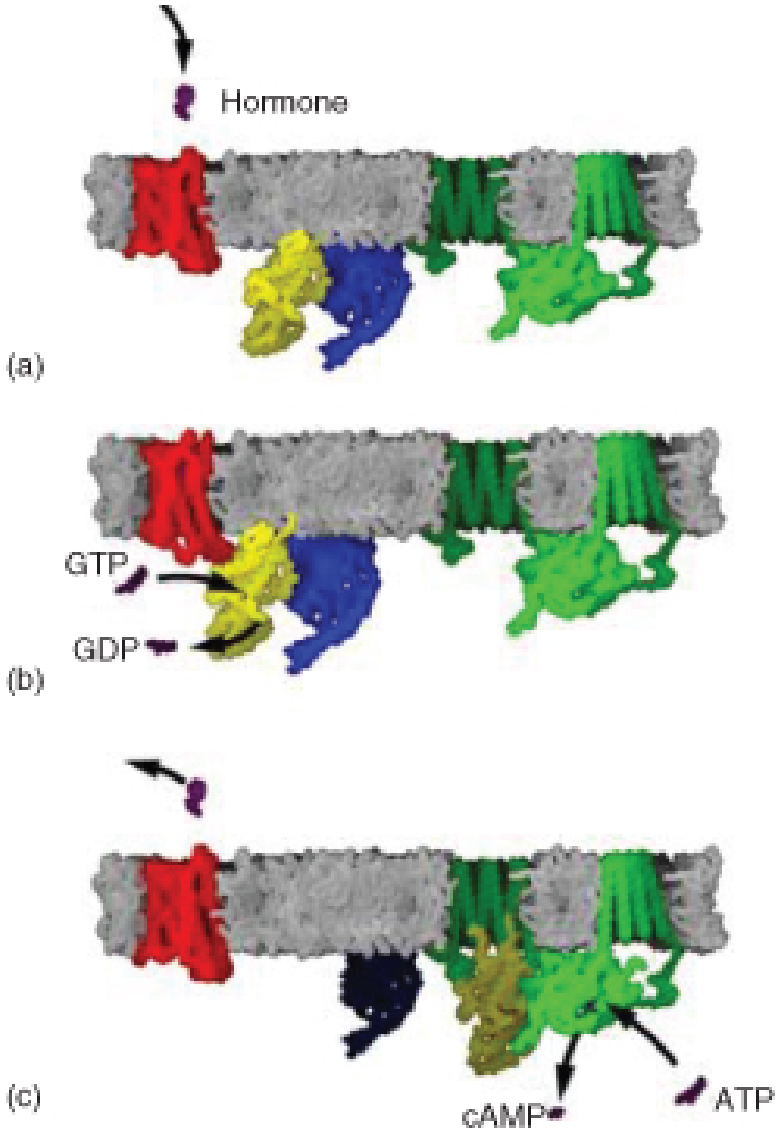


Figure 3.36: How a G-protein linked receptor works with the help of a G-protein. In panel C, the second messenger cAMP can be seen moving away from the enzyme.

G protein-linked receptors are only found in higher eukaryotes, including yeast, plants, and animals. Your senses of sight and smell are dependent on G-protein linked receptors. The ligands that bind to these receptors include light-sensitive compounds, odors, hormones, and neurotransmitters. The ligands for G-protein linked receptors come in different sizes, from small molecules to large proteins. G protein-coupled receptors are involved in many diseases, but are also the target of around half of all modern medicinal drugs.

The process of how a G-protein linked receptor works is outlined in **Figure** 3.36.

Table 3.3:

A.	A ligand such as a hormone (small, purple molecule) binds to the G-linked receptor (red molecule). Before ligand binding, the inactive G-protein (yellow molecule) has GDP bound to it.
B.	The receptor changes shape and activates the G-protein and a molecule of GTP replaces the GDP.
C.	The G-protein moves across the membrane then binds to and activates the enzyme (green molecule). This then triggers the next step in the pathway to the cell's response. After activating the enzyme, the G-protein returns to its original position. The second messenger of this signal transduction is cAMP, as shown in C.

The sensing of the external and internal environments at the cellular level relies on signal transduction. Defects in signal transduction pathways can contribute or lead to many diseases, including cancer and heart disease. This highlights the importance of signal transductions to biology and medicine.

Signal Responses

In response to a signal, a cell may change activities in the cytoplasm or in the nucleus that include the switching on or off of genes. Changes in metabolism, continued growth, movement, or death are some of the cellular responses to signals that require signal transduction.

Gene activation leads to other effects, since the protein products of many of the responding genes include enzymes and factors that increase gene expression. Gene expression factors produced as a result of a cascade can turn on even more genes. Therefore one stimulus can trigger the expression of many genes, and this in turn can lead to the activation of many complex events. In a multicellular organism these events include the increased uptake of glucose from the blood stream (stimulated by insulin), and the movement of neutrophils to sites of infection (stimulated by bacterial products). The set of genes and the order in which they are activated in response to stimuli are often called a genetic program.

Lesson Summary

- Molecules and ions cross the plasma membrane either by passive transport or active the transport.
- Passive transport is the movement of molecules across the cell membrane without an input of energy from the cell.
- Diffusion is the movement of molecules or ions from an area of high concentration to an area of lower concentration. The molecules keep moving down the concentration gradient until equilibrium is reached.
- Osmosis is the diffusion of water molecules across a semipermeable membrane and down a concentration gradient. They can move into or out of a cell, depending on the concentration of the solute.
- Active transport moves molecules across a cell membrane from an area of lower concentration to an area of higher concentration. Active transport requires the use of energy.
- The active transport of small molecules or ions across a cell membrane is generally carried out by transport proteins that are found in the membrane.
- The sodium-potassium pump is an example of a cell membrane pump. It moves three sodium ions out of the cell and two potassium ions into the cell. The sodium-potassium pump uses ATP.
- Endocytosis and exocytosis are active transport mechanisms in which large molecules enter and leave the cell inside vesicles.
- In endocytosis, a substance or particle from outside the cell is engulfed by the cell membrane. The membrane folds over the substance and it becomes completely enclosed by the membrane. There are two main kinds of endocytosis: pinocytosis and phagocytosis.
- Communication between cells is important for coordinating cell function in an organism. Membrane proteins and vesicles are involved in cellular communication.

Review Questions

1. Identify the two ways that particles cross the plasma membrane.
2. How does osmosis differ from diffusion?
3. Outline how the sodium-potassium pump works.
4. Are vesicles involved in passive transport? Explain.
5. What is the difference between endocytosis and exocytosis?
6. Why is pinocytosis (cellular drinking) a form of endocytosis?
7. Identify which type of feedback mechanism is most common in homeostasis, and give an example of that type.
8. Imagine you have discovered a new cell that has not been seen before. How would you go about identifying it based on its structure alone?
9. Homeostasis can be thought of as a dynamic equilibrium rather than an unchanging

state. Do you agree with this statement? Explain your answer.

10. This image shows plant cells. The central vacuole of each cell has shrunk and is smaller than normal. What is the likely solute concentration of the cells' environment which has caused this change?

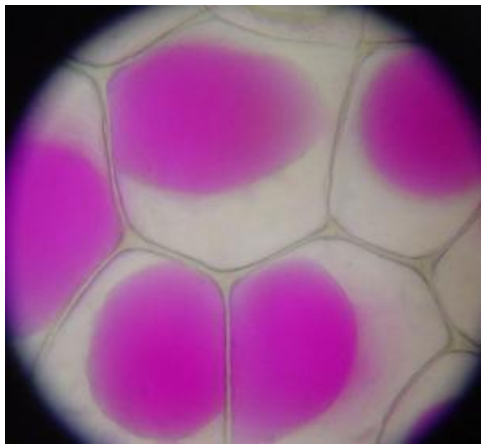


Figure 3.37

Further Reading / Supplemental Links

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- http://fig.cox.miami.edu/~cmallery/150/unity/cell.text.htm
- http://en.wikipedia.org

Vocabulary

active transport The energy-requiring process of pumping molecules and ions across membranes against a concentration gradient.

carrier protein A transport protein that is specific for an ion, molecule, or group of substances; carries the ion or molecule across the membrane by changing shape after the binding of the ion or molecule.

channel protein A transport protein that acts like a pore in the membrane that lets water molecules or small ions through quickly.

contractile vacuole A type of vacuole that removes excess water from a cell.

diffusion The movement of molecules from an area of high concentration of the molecules to an area with a lower concentration.

endocytosis The process of capturing a substance or particle from outside the cell by engulfing it with the cell membrane.

exocytosis The process of vesicles fusing with the plasma membrane and releasing their contents to the outside of the cell.

facilitated diffusion The diffusion of solutes through transport proteins in the plasma membrane.

gated channel protein A transport protein that opens a "gate," allowing a molecule to flow through the membrane.

ion channel A protein that transports ions across the membrane by facilitated diffusion.

ligand A small molecule that binds to a larger molecule.

osmosis The diffusion of water molecules across a selectively permeable membrane from an area of higher concentration to an area of lower concentration.

passive transport A way that small molecules or ions move across the cell membrane without input of energy by the cell.

second messenger A small molecule that starts a change inside a cell in response to the binding of a specific signal to a receptor protein.

selectively permeable The characteristic of the cell membrane that allows certain molecules to pass through the membrane, but not others.

signal-transduction pathway The signaling mechanism by which a cell changes a signal on it surface into a specific response inside the cell; most often involves an ordered sequence of chemical reactions inside the cell which is carried out by enzymes and other molecules.

sodium-potassium pump A carrier protein that moves sodium and potassium ions against large concentration gradients, moves two potassium ions into the cell where potassium levels are high, and pumps three sodium ions out of the cell and into the extracellular fluid.

transport protein A protein that completely spans the membrane, and allows certain molecules or ions to diffuse across the membrane; channel proteins, gated channel proteins, and carrier proteins are three types of transport proteins that are involved in facilitated diffusion.

Points to Consider

Next we turn our attention to photosynthesis.

- What is photosynthesis?
- Where to plants get the "food" they need?
- Where does most of the energy come from?

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Chapter 4

Photosynthesis

4.1 Lesson 4.1: Energy for Life: An Overview of Photosynthesis

Lesson Objectives

- Identify the kind of energy which powers life.
- Contrast the behavior of energy to that of materials in living systems.
- Analyze the way in which autotrophs obtain energy and evaluate the importance of autotrophs to energy for all life.
- Explain the relationship between autotrophs and heterotrophs.
- Discuss the importance of glucose to all life on earth.
- Compare the energy-carrying role of ATP to that of glucose.
- Explain the roles of chlorophyll and NADPH as sources of energy for life.
- Summarize the process of photosynthesis and write out the overall chemical equation for photosynthesis.
- Identify reactants, necessary conditions, and products in the chemical equation for photosynthesis.
- Describe the roles of chlorophyll and chloroplasts in photosynthesis.
- Identify the groups of organisms which are capable of photosynthesis.
- Discuss the many reasons photosynthesis is important to humans.

Introduction

All living things require an ongoing source of energy to do the work of life. You often see energy in action on a large scale: a whale breaches, apple blossoms swell and burst, a firefly glows, or an inky cap mushrooms overnight. However, energy works constantly to maintain

life on a very small scale as well. Inside each cell of every organism, energy assembles chains of information and constructs cellular architecture. It moves tiny charged particles and giant protein molecules. Moreover, it builds and powers cell systems for awareness, response, and reproduction. All life's work requires energy.

Physics tells us that organized systems, such as living organisms, tend to disorder without a constant input of energy. You have direct, everyday experience with this law of nature: after a week of living in your room, you must spend energy in order to return it to its previous, ordered state. Tides and rain erode your sandcastles, so you must work to rebuild them. And your body, after a long hike or big game, must have more fuel to keep going. Living things show amazing complexity and intricate beauty, but if their source of energy fails, they suffer injury, illness, and eventually death.

Physics also tells us that, although energy can be captured or transformed, it inevitably degrades, becoming heat, a less useful form of energy. This is why organisms require a constant input of energy; the work they must do uses up the energy they take in. Energy, unlike materials, cannot be recycled. The story of life is a story of energy flow – its capture, transformation, use for work, and loss as heat.

Energy, the ability to do work, can take many forms: heat, nuclear, electrical, magnetic, light, and chemical energy. Life runs on **chemical energy** - the energy stored in covalent bonds between atoms in a molecule. Where do organisms get their chemical energy? That depends…

How Do Organisms Get Energy? Autotrophs vs. Heterotrophs

Living organisms obtain chemical energy in one of two ways.

Autotrophs, shown in **Figure** 4.1, store chemical energy in carbohydrate food molecules they build themselves. **Food** is chemical energy stored in organic molecules. Food provides both the energy to do work and the carbon to build bodies. Because most autotrophs transform sunlight to make food, we call the process they use **photosynthesis**. Only three groups of organisms - plants, algae, and some bacteria - are capable of this life-giving energy transformation. Autotrophs make food for their own use, but they make enough to support other life as well. Almost all other organisms depend absolutely on these three groups for the food they produce. The **producers**, as autotrophs are also known, begin **food chains** which feed all life. Food chains will be discussed in the *Principles of Ecology* chapter.

Heterotrophs cannot make their own food, so they must eat or absorb it. For this reason, heterotrophs are also known as **consumers**. Consumers include all animals and fungi and many protists and bacteria. They may consume autotrophs, or other heterotrophs or **organic molecules** from other organisms. Heterotrophs show great diversity and may appear far more fascinating than producers. But heterotrophs are limited by our utter dependence on

those autotrophs which originally made our food. If plants, algae, and autotrophic bacteria vanished from earth, animals, fungi, and other heterotrophs would soon disappear as well. All life requires a constant input of energy. Only autotrophs can transform that ultimate, solar source into the chemical energy in food which powers life, as shown in **Figure** 4.2.

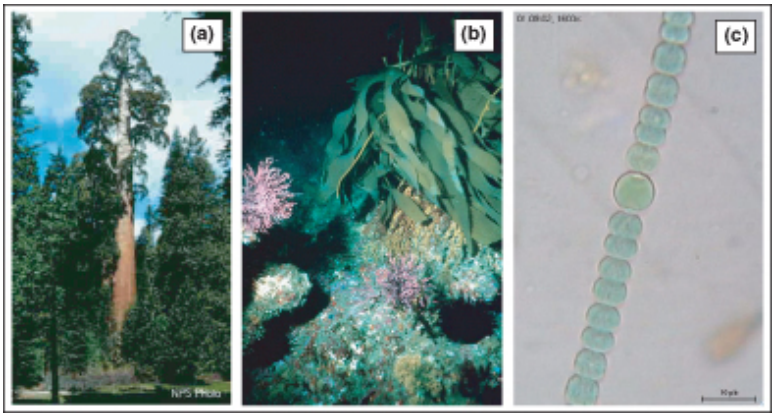


Figure 4.1: Photosynthetic autotrophs, which make food for more than 99% of the organisms on earth, include only three groups of organisms: plants such as the redwood tree (a), algae such as kelp (b), and certain bacteria like this (c).

Photosynthesis provides over 99 percent of the energy supply for life on earth. A much smaller group of autotrophs - mostly bacteria in dark or low-oxygen environments - produce food using the chemical energy stored in **inorganic molecules** such as hydrogen sulfide, ammonia, or methane. While photosynthesis transforms light energy to chemical energy, this alternate method of making food transfers chemical energy from inorganic to organic molecules. It is therefore called **chemosynthesis**, and is characteristic of the tubeworms shown in **Figure** 4.3. Some of the most recently discovered chemosynthetic bacteria inhabit deep ocean hot water vents or "black smokers." There, they use the energy in gases from the Earth's interior to produce food for a variety of unique heterotrophs: giant tube worms, blind shrimp, giant white crabs, and armored snails. Some scientists think that chemosynthesis may support life below the surface of Mars, Jupiter's moon, Europa, and other planets as well. Ecosystems based on chemosynthesis may seem rare and exotic, but they too illustrate the absolute dependence of heterotrophs on autotrophs for food.

Food and Other Energy-Carrying Molecules

You know that the fish you had for lunch contained protein molecules. But do you know that the atoms in that protein could easily have formed the color in a dragonfly's eye, the heart of a water flea, and the whiplike tail of a *Euglena* before they hit your plate as sleek fish muscle? As you learned above, food consists of organic (carbon-containing) molecules which store energy in the chemical bonds between their atoms. Organisms use the atoms of food molecules to build larger organic molecules including proteins, DNA, and fats and

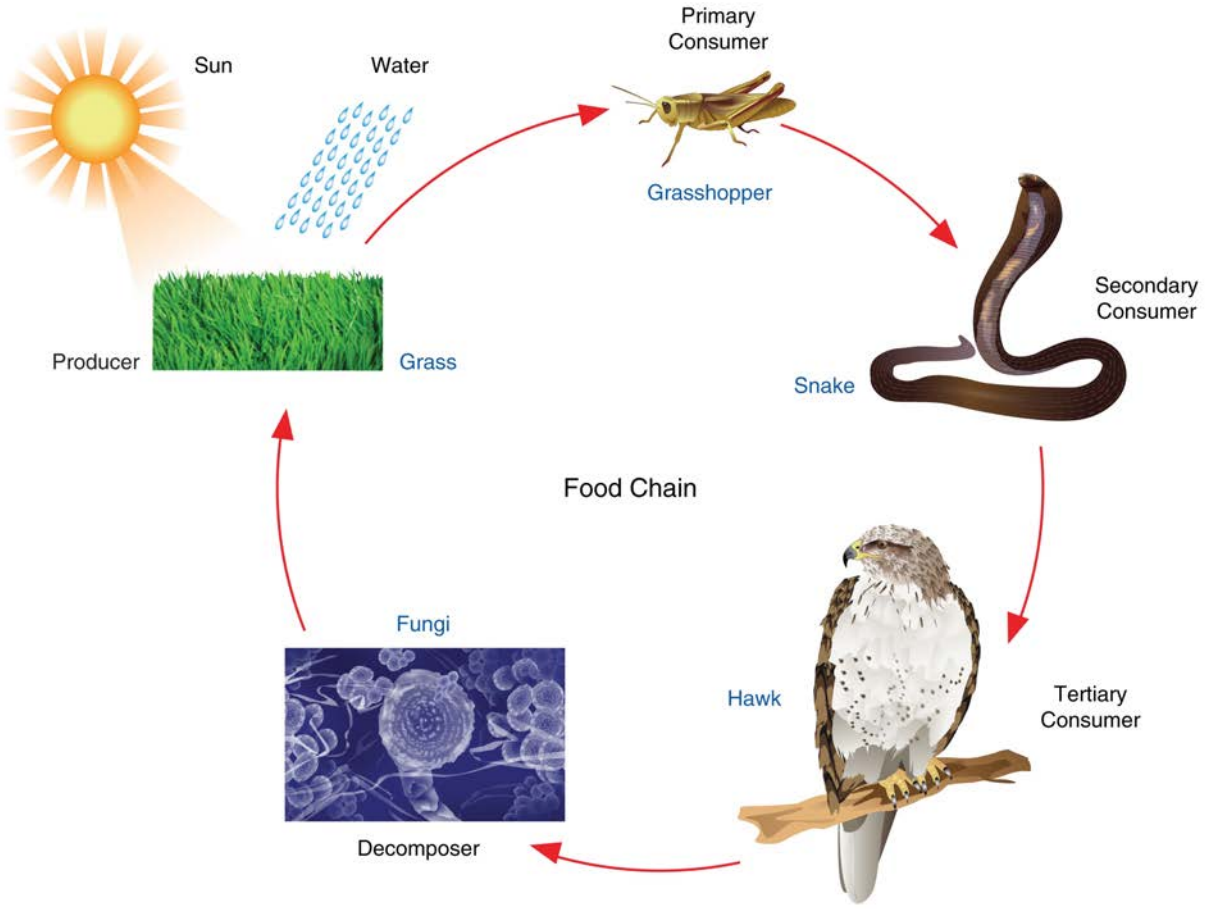


Figure 4.2: Food chains carry energy from producers (autotrophs) to consumers (heterotrophs). 99 percent of energy for life comes from the sun via photosynthesis. Note that only nutrients recycle. Energy must continue to flow into the system.

Figure 4.3: Tubeworms deep in the Gulf of Mexico get their energy from chemosynthetic bacteria living within their tissues. No digestive systems needed! Photo: Charles Fisher

use the energy in food to power life processes. By breaking the bonds in food molecules, cells release energy to build new compounds. Although some energy dissipates as heat at each energy transfer, much of it is stored in the newly made molecules. Chemical bonds in organic molecules are a reservoir of the energy used to make them. Fueled by the energy from food molecules, cells can combine and recombine the elements of life to form thousands of different molecules. Both the energy (despite some loss) and the materials (despite being reorganized) pass from producer to consumer – perhaps from algal tails, to water flea hearts, to dragonfly eye colors, to fish muscle, to you!

The process of photosynthesis, which usually begins the flow of energy through life, uses many different kinds of energy-carrying molecules to transform sunlight energy into chemical energy and build food.

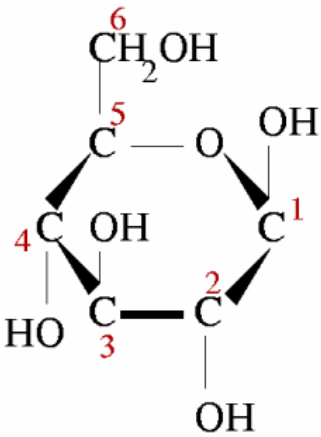
Some carrier molecules hold energy briefly, quickly shifting it like a hot potato to other molecules. This strategy allows energy to be released in small, controlled amounts. An example is **chlorophyll,** the green pigment present in most plants which helps convert solar energy to chemical energy. When a chlorophyll molecule absorbs light energy, electrons are excited and "jump" to a higher energy level. The excited electrons then bounce to a series of carrier molecules, losing a little energy at each step. Most of the "lost" energy powers some small cellular task, such as moving ions across a membrane or building up another molecule. Another short-term energy carrier important to photosynthesis, NADPH, holds chemical energy a bit longer but soon "spends" it to help to build sugar.

Two of the most important energy-carrying molecules are **glucose** and **ATP**, adenosine triphosphate. These are nearly universal fuels throughout the living world and both are also key players in photosynthesis, as shown below.

A molecule of glucose, which has the chemical formula $C_6H_{12}O_6$, carries a packet of chemical energy just the right size for transport and uptake by cells. In your body, glucose is the "deliverable" form of energy, carried in your blood through capillaries to each of your 100 trillion cells. Glucose is also the carbohydrate produced by photosynthesis, and as such is the near-universal food for life.

ATP molecules store smaller quantities of energy, but each releases just the right amount to actually do work within a cell. Muscle cell proteins, for example, pull each other with the energy released when bonds in ATP break open (discussed below). The process of photosynthesis also makes and uses ATP - for energy to build glucose! ATP, then, is the useable form of energy for your cells.

Glucose is the energy-rich product of photosynthesis, a universal food for life. It is also the primary form in which your bloodstream delivers energy to every cell in your body. The six carbons are numbered.



Why do we need both glucose and ATP? Why don't plants just make ATP and be done with it? If energy were money, ATP would be a quarter. Enough money to operate a parking meter or washing machine. Glucose would be a dollar bill (or $10) – much easier to carry around in your wallet, but too large to do the actual work of paying for parking or washing. Just as we find several denominations of money useful, organisms need several "denominations" of energy – a smaller quantity for work within cells, and a larger quantity for stable storage, transport, and delivery to cells.

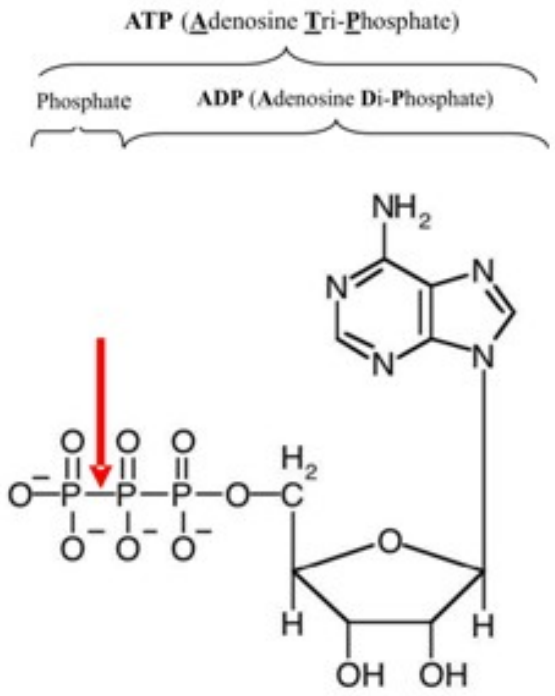
Let's take a closer look at a molecule of ATP. Although it carries less energy than glucose, its structure is more complex. "A" in ATP refers to the majority of the molecule – adenosine – a combination of a nitrogenous base and a five-carbon sugar. "T" and "P" indicate the three phosphates, linked by bonds which hold the energy actually used by cells. Usually, only the outermost bond breaks to release or spend energy for cellular work.

An ATP molecule, shown below, is like a rechargeable battery: its energy can be used by the cell when it breaks apart into ADP (adenosine diphosphate) and phosphate, and then the "worn-out battery" ADP can be recharged using new energy to attach a new phosphate

and rebuild ATP. The materials are recyclable, but recall that energy is not!

How much energy does it cost to do your body's work? A single cell uses about 10 million ATP molecules per second, and recycles all of its ATP molecules about every 20-30 seconds.

A red arrow shows the bond between two phosphate groups in an ATP molecule. When this bond breaks, its chemical energy can do cellular work. The resulting ADP molecule is recycled when new energy attaches another phosphate, rebuilding ATP.



Keep these energy-carrying molecules in mind as we look more carefully at the process which originally captures the energy to build them: photosynthesis. Recall that it provides nearly all of the food (energy and materials) for life. Actually, as you will see, we are indebted to photosynthesis for even more than just the energy and building blocks for life.

Photosynthesis: The Most Important Chemical Reaction for Life on Earth

What do pizza, campfires, dolphins, automobiles, and glaciers have in common? In the following section, you'll learn that all five rely on photosynthesis, some in more ways than one. Photosynthesis is often considered the most important chemical reaction for life on earth. Let's delve into how this process works and why we are so indebted to it.

Photosynthesis involves a complex series of chemical reactions, each of which convert one substance to another. These reactions taken as a whole can be summarized in a single

symbolic representation – as shown in the chemical equation below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Chlorophyll}]{\text{Chloroplast}}{\text{Enzymes}} C_6H_{12}O_6 + 6O_2$$

We can substitute words for the chemical symbols. Then the equation appears as below.

$$\text{Carbon dioxide} + \text{water} + \text{light energy} \xrightarrow[\text{Chlorophyll}]{\text{Chloroplast}}{\text{Enzymes}} \text{glucose} + \text{oxygen gas}$$

Like all chemical equations, this equation for photosynthesis shows reactants connected by plus signs on the left and products, also connected by plus signs, on the right. An arrow indicating the process or chemical change leads from the reactants to the products, and conditions necessary for the chemical reaction are written above the arrow. Note that the same kinds of atoms, and number of atoms, are found on both sides of the equation, but the kinds of compounds they form change.

You use chemical reactions every time you cook or bake. You add together ingredients (the reactants), place them in specific conditions (often heat), and enjoy the results (the products). A recipe for chocolate chip cookies written in chemical equation form is shown below.

$$\underbrace{\text{Butter} + \text{sugar} + \text{eggs} + \text{flour} + \text{chocolate chips}}_{\text{REACTANTS}} \xrightarrow[\text{8—10 minutes}]{\text{375 F}} \underbrace{\text{chocolate chip cookies}}_{\text{PRODUCT}}$$

NECESSARY CONDITIONS

Compare this familiar recipe to photosynthesis below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Chlorophyll}]{\text{Chloroplast}}{\text{Enzymes}} C_6H_{12}O_6 + 6O_2$$

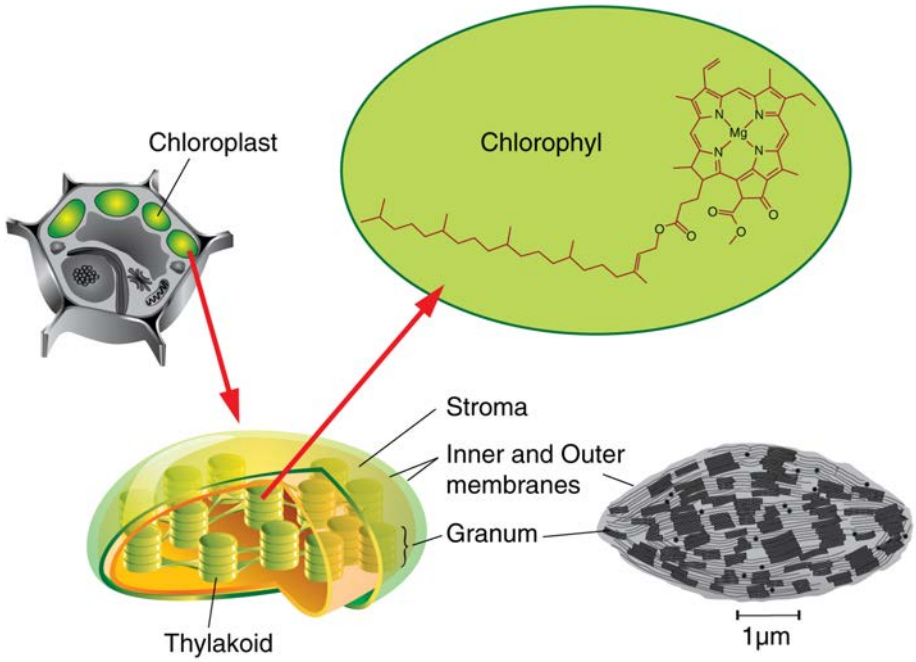
The equation shows that the "ingredients" for photosynthesis are carbon dioxide, water, and light energy. Plants, algae, and photosynthetic bacteria take in light from the sun, molecules of carbon dioxide from the air, and water molecules from their environment and combine these reactants to produce food (glucose).

Of course, light, carbon dioxide, and water mix in the air even without plants. But they do not chemically change to make food without very specific necessary conditions which are found only in the cells of photosynthetic organisms. Necessary conditions include:

1. **enzymes** - proteins which speed up chemical reactions without the heat required for

cooking
2. **chlorophyll** - a pigment which absorbs light
3. **chloroplasts** - organelles whose membranes embed chlorophyll, accessory pigments, and enzymes in patterns which maximize photosynthesis

Within plant cells or algal cells, chloroplasts organize the enzymes, chlorophyll, and accessory pigment molecules necessary for photosynthesis.



When the reactants meet inside chloroplasts, or the very similar cells of blue-green bacteria, chemical reactions combine them to form two products: energy-rich glucose molecules and molecules of oxygen gas. Photosynthetic organisms store the glucose (usually as starch) and release the oxygen gas into the atmosphere as waste.

Let's review the chemical equation for photosynthesis once more, this time at the level of atoms as in the equation below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Chlorophyll}]{\text{Chloroplast}}{}^{\text{Enzymes}} C_6H_{12}O_6 + 6O_2$$

Look closely at its primary purpose: storing energy in the chemical bonds of food molecules. The source of energy for food is sunlight energy. The source of carbon atoms for the food molecules is carbon dioxide from the air, and the source of hydrogen atoms is water. Inside the cells of plants, algae, and photosynthetic bacteria, chlorophyll, and enzymes use the light energy to rearrange the atoms of the reactants to form the products, molecules of glucose and oxygen gas. Light energy is thus transformed into chemical energy, stored in the bonds

which bind six atoms each of carbon and oxygen to twelve atoms of hydrogen – forming a molecule of glucose. This energy rich carbohydrate molecule becomes food for the plants, algae, and bacteria themselves as well as for the heterotrophs which feed on them.

One last detail: why do "6"s precede the CO_2, H_2O, and O_2? Look carefully, and you will see that this "balances" the equation: the numbers of each kind of atom on each side of the arrow are equal. Six molecules each of CO_2 and H_2O make 1 molecule of glucose and 6 molecules of oxygen gas.

Lesson Summary

All organisms require a constant input of **energy** to do the work of life.

- Energy cannot be recycled, so the story of life is a story of energy flow – its capture, transformation, use for work, and loss as heat.

Life runs on **chemical energy**.

- **Food** is chemical energy stored in organic molecules.
- Food provides both the energy to do life's work and the carbon to build life's bodies.
- The carbon cycles between organisms and the environment, but the energy is "spent" and must be replaced.

Organisms obtain chemical energy in one of two ways.

- **Autotrophs** make their own carbohydrate foods, transforming sunlight in **photosynthesis** or transferring chemical energy from inorganic molecules in **chemosynthesis**.
- **Heterotrophs** consume organic molecules originally made by autotrophs.
- All life depends absolutely upon autotrophs to make food molecules.

The process of **photosynthesis** produces more than 99% of all food for life, forming the foundation of most food chains.

- Only three groups of organisms – plants, algae, and some bacteria – carry out the process of photosynthesis.

All organisms use similar energy-carrying molecules for food and to carry out life processes.

- **Glucose** ($C_6H_{12}O_6$,) is a nearly universal fuel delivered to cells, and the primary product of photosynthesis.

- **ATP** molecules store smaller amounts of energy and are used within cells to do work.
- **Chlorophyll** and **NADPH** molecules hold energy temporarily during the process of photosynthesis.

The chemical equation below summarizes the many chemical reactions of photosynthesis.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Chlorophyll}]{\text{Chloroplast}}{}^{\text{Enzymes}} C_6H_{12}O_6 + 6O_2$$

- The equation states that the reactants (carbon dioxide, water and light), in the presence of chloroplasts, chlorophyll and enzymes, yield two products, glucose and oxygen gas.
- **Chlorophyll** is a pigment that absorbs sunlight energy.
- **Chloroplasts** are the organelles within plant and algal cells that organize enzymes and pigments so that the chemical reactions proceed efficiently.

In the process of photosynthesis, plants, algae, and blue green bacteria absorb sunlight energy and use it to change carbon dioxide and water into glucose and oxygen gas.

- Glucose contains stored chemical energy and provides **food** for the organisms that produce it and for many heterotrophs.
- Photosynthesized carbohydrates (represented here by glucose) make up the wood we burn and (over hundreds of millions of years) the coal, oil, and gas we now use as fossil fuels.
- Most of the oxygen gas is waste for the organisms which produce it.
- Both CO_2 consumed and O_2 produced affect the composition of earth's atmosphere; before photosynthesis evolved, oxygen was not part of the atmosphere.

Review Questions

1. Compare the behavior of energy to the behavior of matter in living systems.
2. Water and carbon dioxide molecules are reactants in the process of photosynthesis. Does this mean they are "food" for plants, algae, and blue-green bacteria? Use the definition of "food" to answer this question.
3. Compare autotrophs to heterotrophs, and describe the relationship between these two groups of organisms.
4. Name and describe the two types of food making found among autotrophs, and give an example of each. Which is quantitatively more important to life on earth?
5. Trace the flow of energy through a typical food chain (describing "what eats what"), including the original source of that energy and its ultimate form after use. Underline each form of energy or energy-storing molecule, and boldface each process which transfers or transforms energy.

6. Trace the pathway that carbon atoms take through a typical food chain, beginning with their inorganic source.
7. The fact that all organisms use similar energy-carrying molecules shows one aspect of the grand "Unity of Life." Name two universal energy-carrying molecules, and explain why most organisms need both carriers rather than just one.
8. A single cell uses about 10 million ATP molecules per second. Explain how cells use the energy and recycle the materials in ATP.
9. Discuss the importance of photosynthesis to humans in terms of food, fuel, and atmosphere. In what ways could you affect the process of photosynthesis to conserve these benefits?
10. Using symbols, write the overall chemical equation for photosynthesis, labeling the reactants, necessary conditions, and products. Then write two complete sentences which trace the flow of (1) energy and (2) atoms from reactants to products.

Further Reading / Supplemental Links

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- Illustrator: Thomas Porostocky; Writer: Lee Billings; Map data adapted from MODIS observations by NASA's Terra and Aqua satellites; Graph data and reference: Biology, 4th ed., Neil A. Campbell, Benjamin/Cummings Publishing Company, 1996. "Crib Sheet #10, Photosynthesis." *Seed Magazine,* August 2007. Available on the Web at:
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- http://vcell.ndsu.nodak.edu/animations/photosynthesis/index.htm.

Vocabulary

ATP Adenosine triphosphate, the energy-carrying molecule used by cells to do work.

autotroph An organism capable of transforming one form of energy – usually light – into the food, or stored chemical energy, they need to do work.

chemosynthesis Process by which a type of autotroph makes food using chemical energy in inorganic molecules.

chlorophyll The primary pigment of photosynthesis.

chloroplast The organelle in plant and algal cells where photosynthesis takes place.

consumers Heterotrophs, which must eat or absorb organic food molecules because they are incapable of producing them.

energy The ability to do work.

food Organic (carbon-containing) molecules which store energy in the chemical bonds between their atoms.

food chain A pathway which traces energy flow from producers through consumers.

glucose The carbohydrate product of photosynthesis; serves as the universal fuel for life.

heat Thermal energy, the energy of vibrations in molecules – the "lowest" form of energy, which cannot easily be used for useful work.

heterotrophs Organisms which must consume organic molecules because they are incapable of synthesizing the food, or stored chemical energy, they need to work.

inorganic molecules Molecules which do not contain carbon (with a few exceptions such as carbon dioxide) and are not necessarily made by living organisms.

NADPH An energy carrier molecule produced in the light reactions of photosynthesis and used to build sugar in the Calvin cycle.

organic molecule A molecule which contains carbon, made by living organisms; examples include carbohydrates, lipids, and proteins.

photosynthesis The process by which plants, algae, and some bacteria transform sunlight into chemical energy and use it to produce carbohydrate food and oxygen for almost all life.

producer An autotroph, capable of synthesizing food molecules; forms basis of food chains.

Points to Consider

- Why do some people describe photosynthesis by plants as "making food from thin air"?
- Before we conclude this analysis of "the most important chemical reaction for life on Earth," solidify your understanding of its importance by returning to the pizza, campfires, dolphins, automobiles, and glaciers. Can you connect them all to the chemical equation for photosynthesis (**Figure** 4.4)?
- You'll be able to make more connections after studying the next chapter on cellular respiration. Can you already connect carbon dioxide and oxygen to automobiles?

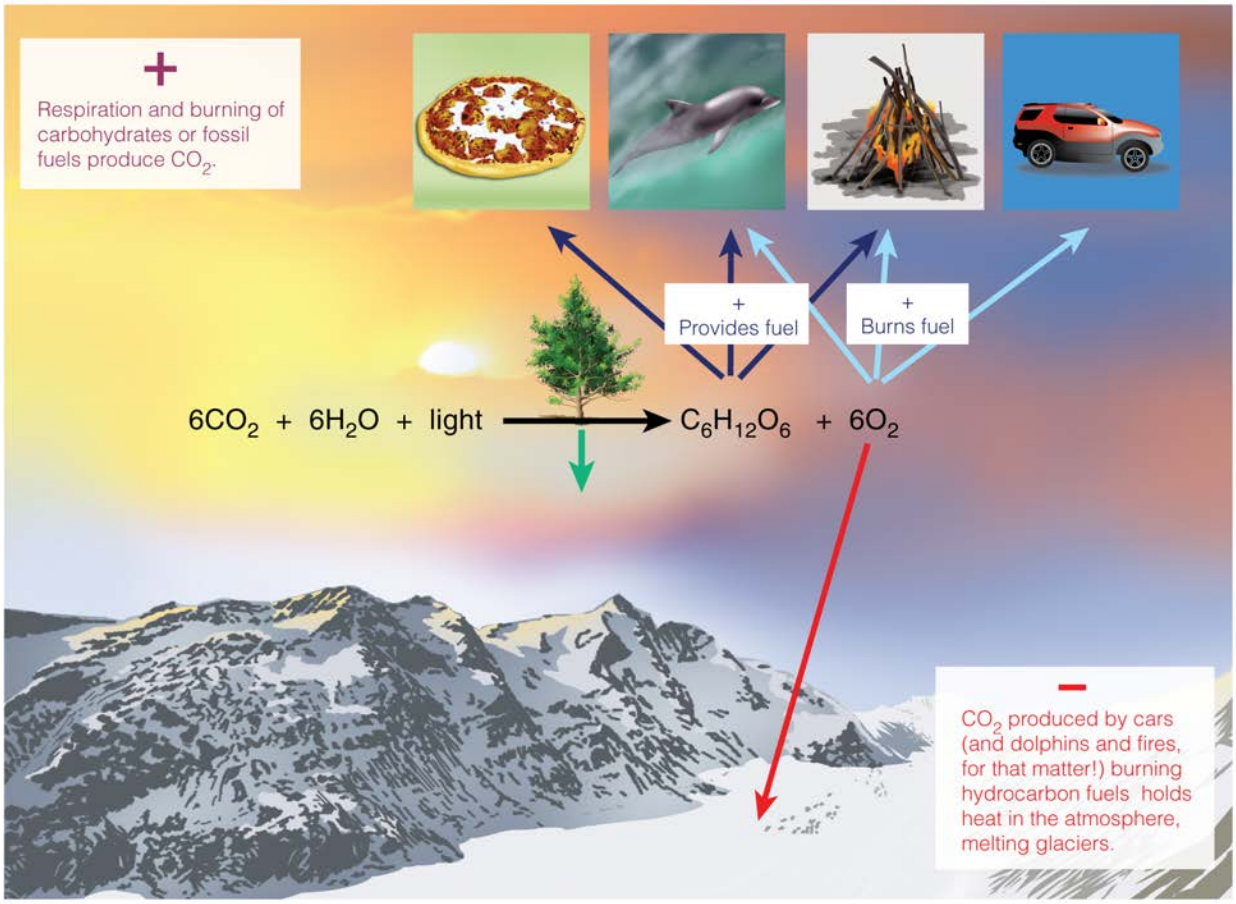

+
Respiration and burning of carbohydrates or fossil fuels produce CO_2.
+
Provides fuel
+
Burns fuel
$6CO_2 + 6H_2O + light \rightarrow C_6H_{12}O_6 + 6O_2$
–
CO_2 produced by cars (and dolphins and fires, for that matter!) burning hydrocarbon fuels holds heat in the atmosphere, melting glaciers.

Figure 4.4

4.2 Lesson 4.2: Into the Chloroplast: How Photosynthesis Works

Lesson Objectives

- Understand that hundreds of years of scientific exploration have contributed to our understanding of photosynthesis.
- Explain the contributions of Van Helmont, Priestley, and Melvin Calvin to our understanding of photosynthesis.
- Describe the structure and function of chloroplasts, thylakoids, and pigments.
- Explain how electron carrier molecules form electron transport chains.
- Trace the flow of energy and materials through the Light Reactions, including chemiosmosis.
- Trace the flow of energy and materials through The Calvin Cycle.
- Compare and contrast C-3, C-4, and CAM pathways for carbon fixation.

Introduction

Life requires photosynthesis for fuel and for the oxygen to burn that fuel. Since the Industrial Revolution (late 18th and early 19th centuries), we humans have relied on products of ancient photosynthesis for enormous quantities of fossil fuel energy. And, knowingly or not, we have also benefited from photosynthesis to remove the carbon dioxide produced when we burn those fuels. So it may not surprise you that biologists have studied this critical process in great detail. The goals of this lesson are:

- to discuss how scientists have explored this most important chemical reaction for life on earth
- to encourage you to appreciate just a little of its intricate beauty, and
- to understand how your own decisions and actions can influence the process of photosynthesis.

You've learned that a single chemical reaction represents the overall process of photosynthesis as demonstrated in the equation below.

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} + \underset{\text{light energy}}{\text{light}} \xrightarrow[\text{enzymes}]{\text{Chloroplast, Chlorophyll}} \underset{\substack{\text{glucose} \\ \text{(stored chemical energy)}}}{C_6H_{12}O_6} + \underset{\text{oxygen gas}}{6O_2}$$

Although photosynthesis may seem straightforward in this form, such simplicity is deceiving for two reasons. First, the equation above summarizes dozens of individual chemical reactions

involving many intermediate compounds. And second, just discovering major players like CO_2 and O_2 was challenging, because our ordinary senses cannot detect these molecules in "thin air!"

How do we know that the chemical reaction in photosynthesis really happens? Two famous historical experiments help us begin to understand this process.

Figure 4.5: In the 17 century, Jan Van Helmont, a Flemish chemist, physiologist, and physician, weighed and potted a willow tree, showing that plants do not get food from the soil.

In the 17^{th} century, people who thought about it at all assumed that plants get their food from the soil. Many people, encouraged by sellers of "plant food," still do. In 1638, Jan Baptist Van Helmont planted a 5 pound willow tree, like the one shown in **Figure** 4.5, in a 200 pound tub of soil. After 5 years of watering the plant, he weighed both again. The willow had gained over 160 pounds, but the soil had lost only 2 ounces. Van Helmont concluded that plants do not get their materials from soil, and inferred that they grow using materials from water (which he did not measure). As you know now, he was half right. Although soil provides important nutrients to plants, it supplies neither the energy nor the vast majority of the materials to build the plant. We must excuse him, because no one in the 17^{th} century knew that carbon atoms form the basis of life, or that they float around in air in the form of carbon dioxide.

In the late 1770s, minister and natural philosopher Joseph Priestley burned a candle in a jar of air and observed that the candle burned out long before it ran out of wax. A similar experiment with a mouse resulted in the mouse's death. Priestley suggested that animals,

like candles, "injure" the air. Adding a mint plant, as shown in **Figure** 4.6, however, "restored" the air which had been "injured" by the mouse or the candle. Only later, after many chemistry experiments, did Priestley publish his discovery of "dephlogisticated air." But in his studies of mice, plants, and candles, he had shown that plants produce, and animals consume, oxygen gas.

Figure 4.6: Joseph Priestly's bell jar experiment.

During the 20th century, we learned that photosynthesis involves much more than just the three reactants, the three necessary conditions, and the two products shown in the equation. Using powerful microscopes, we've narrowed the process to one type of organelle within the plant – the chloroplast. In the next section, you will learn in more detail just how plants, algae, and photosynthetic bacteria make food for us all "from thin air." First, let's look at the organelle in which the drama of photosynthesis takes place and meet some of the key actors.

For a detailed animation of the complete photosynthesis process, see http://vcell.ndsu.edu/animations/photosynthesis/first.htm.

Chloroplasts: Theaters for Photosynthesis

If you examine a single leaf of the aquatic plant *Elodea*, shown in **Figure** 4.7, under a microscope, you will see within each cell dozens of small green ovals. These are **chloroplasts**, the organelles which conduct photosynthesis in plants and algae. Chloroplasts closely resemble some types of bacteria and even contain their own circular DNA and ribosomes. In fact, the **endosymbiotic theory** holds that chloroplasts were once independently living bacteria (prokaryotes). So when we say that photosynthesis occurs within chloroplasts, we speak not

only of the organelles within plants and algae, but also of some bacteria – in other words, virtually all photosynthetic autotrophs.

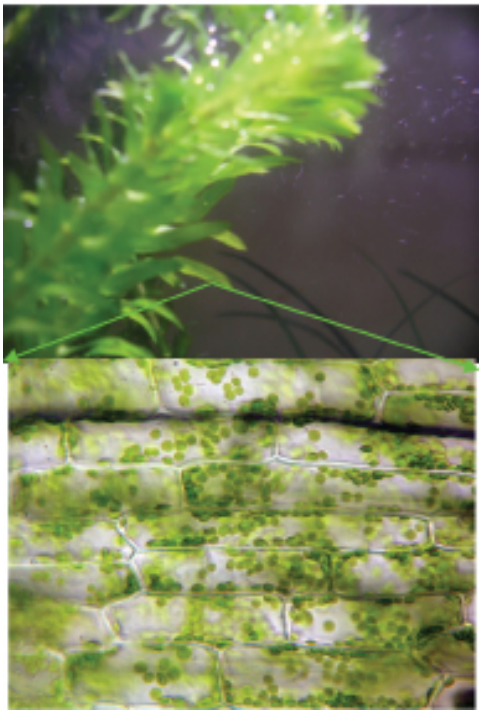


Figure 4.7: (above), like all plants and algae, consists of cells which contain organelles called chloroplasts (green ovals in the microphotograph below). If you look carefully at living cells through a microscope, you may see the chloroplasts moving slowly around the cell edges. The plant itself may not move, but this cyclosis hints at all the action within plant cells.

Both chloroplasts and photosynthetic bacteria contain neat stacks (**grana**) of flattened sac-shaped membrane compartments (**thylakoids**), made in turn of elaborate and highly organized patterns of molecules which conduct photosynthesis, as shown in **Figure** 4.8. In addition to enzymes, two basic types of molecules - **pigments** and **electron carriers** – are key players.

Pigment molecules, often arranged together with proteins in large, complex **photosystems**, absorb specific wavelengths of light energy and reflect others; therefore, they appear colored. The most common photosynthetic pigment is **chlorophyll**, which absorbs blue-violet and red wavelengths of light, and reflects green (**Figure** 4.9 and **Figure** 4.10). **Accessory pigments** absorb other colors of light and then transfer the energy to chlorophyll. These include xanthophylls (yellow) and carotenoids (orange).

Electron carrier molecules are usually arranged in **electron transport chains** (ETCs). These accept and pass along energy-carrying electrons in small steps (**Figure** 4.11). In this way, they produce ATP and NADPH, which temporarily store chemical energy. Electrons

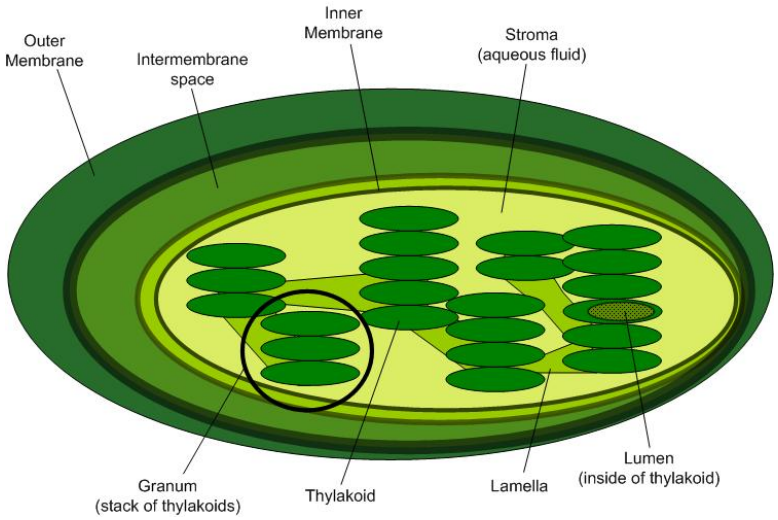


Figure 4.8: The structure of a chloroplast shows how membrane and molecular architecture helps life processes. Stacks of oval compartments (thylakoids) arrange chlorophyll, accessory pigment molecules, and photosynthetic proteins to capture sunlight and allow a concentration of ions within the sacs. You can see the green color of the chlorophyll. You cannot see the electron carriers, sequenced within the sac membranes, but their arrangement helps harvest small amounts of energy from excited electrons.

in transport chains behave much like a ball bouncing down a set of stairs – a little energy is lost with each bounce. However, the energy "lost" at each step in an electron transport chain accomplishes a little bit of work, which eventually results in the synthesis of ATP.

Now that you've met some of the key players and explored the theater, let's put them together to see how the process unfolds. We will divide the process into two basic sets of reactions, known as the light reactions and the Calvin cycle, which uses carbon dioxide. As you study the details, refer frequently to the chemical equation of photosynthesis. In the first stage, you'll discover how chloroplasts transform light energy, and why we owe our ability to breathe to plants!

Photosynthesis Stage I: The Light Reactions: in which Chloroplasts Capture Sunlight Chemical Energy...

Every second, the sun fuses over 600 million tons of hydrogen into 596 tons of helium, converting over 4 tons of helium (4.3 billion kg) into light and heat energy. Countless tiny packets of that light energy travel 93 million miles (150 million km) through space, and about 1% of the light which reaches the Earth's surface participates in photosynthesis. Light is the source of energy for photosynthesis, and the first set of reactions which begin the process requires light – thus the name, Light Reactions, or Light-dependent Reactions.

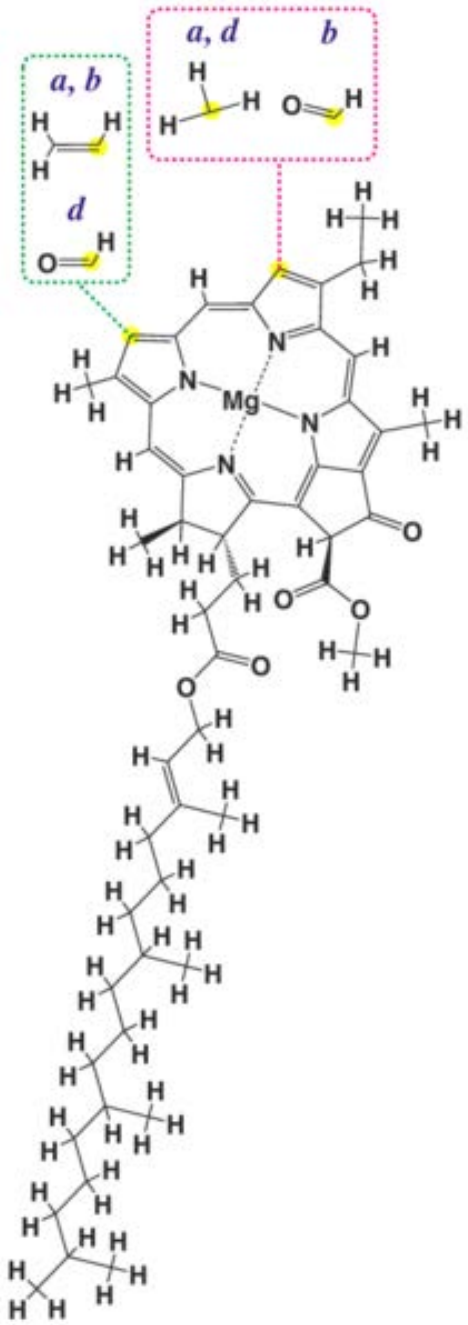


Figure 4.9: The pigment molecule, chlorophyll, appears green because its electrons absorb blue-violet and red light and reflect green, orange, and yellow light. This diagram shows that there are actually several different kinds of chlorophyll (a,b, and d shown here) in plants.

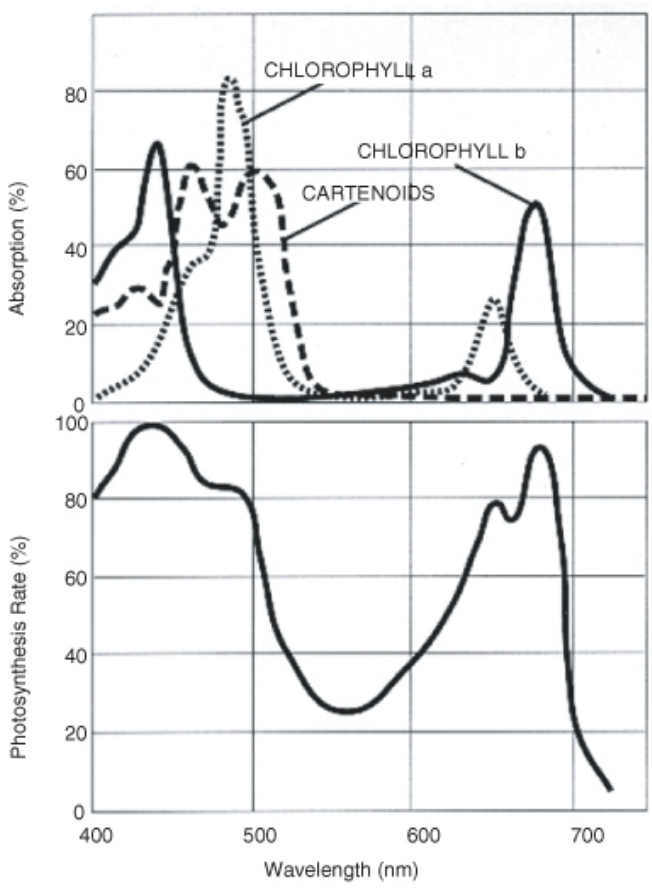


Figure 4.10: Each kind of pigment absorbs specific wavelengths (colors) of light. Sunlight contains many different wavelengths, which you see when they separate into a rainbow. Not all colors of light are used to make food for life. Most plants, algae, and photosynthetic bacteria appear green because they reflect green wavelengths. Their pigments have absorbed the violet-blue and red wavelengths. The amount of photosynthesis depends on the wavelength of light available.

When light strikes chlorophyll (or an accessory pigment) within the chloroplast, it energizes electrons within that molecule. These electrons jump up to higher energy levels; they have absorbed or captured, and now carry, that energy. High-energy electrons are "excited." Who wouldn't be excited to hold the energy for life?

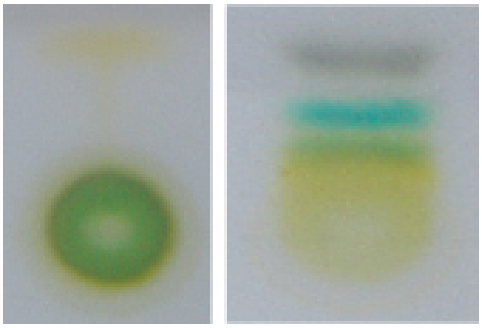


Figure 4.11: If you transfer spinach tissue onto a strip of paper and allow solvent to climb the paper, you can separate the pigment molecules. This technique for seeing molecules is known as chromatography ("color-writing"). The basic concept has many different applications in biochemistry. The images show two stages of a single chromatogram of spinach pigments.

...And Change the Rules of Chemistry for Life!

The excited electrons leave chlorophyll to participate in further reactions, leaving the chlorophyll "at a loss"; eventually they must be replaced. That replacement process also requires light, working with an enzyme complex to split water molecules. In this process of **photolysis** ("splitting by light"), H_2O molecules are broken into hydrogen ions, electrons, and oxygen atoms. The electrons replace those originally lost from chlorophyll. Hydrogen ions and the high-energy electrons from chlorophyll will carry on the energy transformation drama after the Light Reactions are over.

The oxygen atoms, however, form oxygen gas, which is a waste product of photosynthesis (**Figure** 4.12). The oxygen given off supplies most of the oxygen in our atmosphere. Before photosynthesis evolved, Earth's atmosphere lacked oxygen altogether, and this highly reactive gas was toxic to the many organisms living at the time. Something had to change! Most contemporary organisms rely on oxygen for efficient respiration. So plants don't just "restore" the air, as Priestley suggested. They also had a major role in creating it!

To summarize, chloroplasts "capture" sunlight energy in two ways. Light "excites" electrons in pigment molecules, and light provides the energy to split water molecules, providing more electrons as well as hydrogen ions.

Now let's follow those excited electrons…

Nitrogen	78.084%
Oxygen	20.946%
Argon	0.934%
Carbon dioxide	0.038%
Water vapor	1%
Other	0.002%

Figure 4.12: Photosynthesis has made the Earth's atmosphere today very different from what it was 2-3 billion years ago, by giving off oxygen gas as waste. The table to the right shows the composition of today's atmosphere. On the left is an Apollo 17 photograph of Earth.

How Do Chloroplasts Convert Light Energy to Chemical Energy?

Excited electrons which have absorbed light energy are unstable. However, the highly organized **electron carrier** molecules embedded in chloroplast membranes order the flow of these electrons, directing them through electron transport chains (ETCs). At each transfer, small amounts of energy released by the electrons are captured and put to work or stored. Some is also lost as heat with each transfer, but overall the light reactions are extremely efficient at capturing light energy and transforming it to chemical energy.

Two sequential transport chains harvest the energy of excited electrons, as shown in **Figure** 4.13.

(1) First, they pass down an ETC which captures their energy and uses it to pump hydrogen ions by active transport into the thylakoids. These concentrated ions store potential energy by forming a **chemiosmotic** or **electrochemical gradient** – a higher concentration of both positive charge and hydrogen inside the thylakoid than outside. (The gradient formed by the H^+ ions is known as a chemiosmotic gradient.) Picture this energy buildup of H^+ as a dam holding back a waterfall. Like water flowing through a hole in the dam, hydrogen ions "slide down" their concentration gradient through a membrane protein which acts as both ion channel and enzyme. As they flow, the ion channel/enzyme **ATP synthase** uses their energy to chemically bond a phosphate group to ADP, making ATP.

(2) Light re-energizes the electrons, and they travel down a second electron transport chain (ETC), eventually bonding hydrogen ions to $NADP^+$ to form a more stable energy storage molecule, NADPH. NADPH is sometimes called "hot hydrogen," and its energy and hydrogen atoms will be used to help build sugar in the second stage of

photosynthesis.

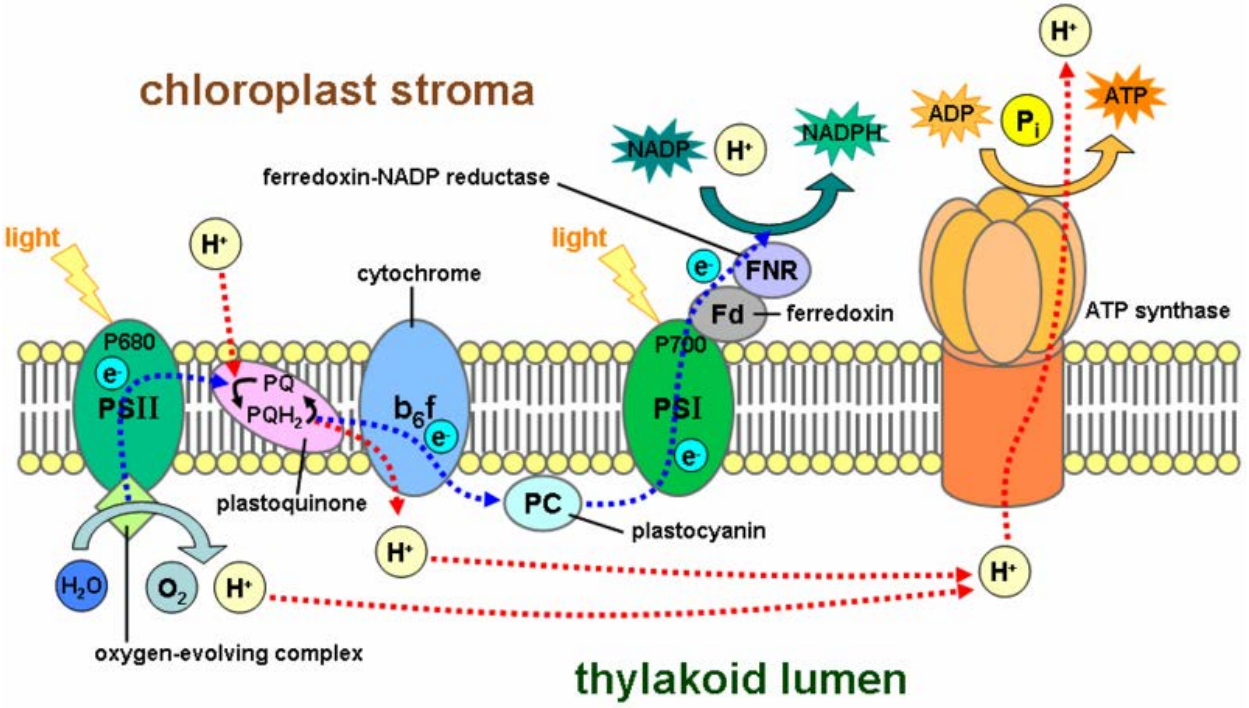


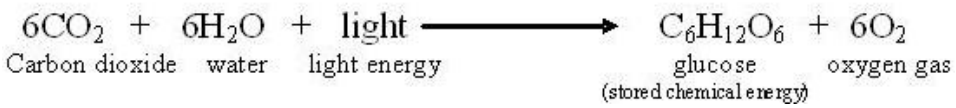
Figure 4.13: Membrane architecture: The large colored carrier molecules form electron transport chains which capture small amounts of energy from excited electrons in order to store it in ATP and NADPH. Follow the energy pathways: light electrons NADPH (blue line) and light electrons concentrated H ATP (red line). Note the intricate organization of the chloroplast.

NADPH and ATP molecules now store the energy from excited electrons – energy which was originally sunlight – in chemical bonds. Thus chloroplasts, with their orderly arrangement of pigments, enzymes, and electron transport chains, transform light energy into chemical energy. The first stage of photosynthesis – **light-dependent reactions** or simply "light reactions" – is complete.

Photosynthesis Stage II: The Calvin Cycle - Making Food "From Thin Air"

You've learned that the first, light-dependent stage of photosynthesis uses two of the three reactants - water and light - and produces one of the products - oxygen gas (a waste product of this process). All three necessary conditions are required – chlorophyll pigments, the chloroplast "theater," and enzyme catalysts. The first stage transforms light energy into

chemical energy, stored to this point in molecules of ATP and NADPH. Look again at the overall equation below. What is left?



Waiting in the wings is one more reactant – carbon dioxide, and yet to come is the star product which is food for all life – glucose. These key players perform in the second act of the photosynthesis drama, in which food is "made from thin air!"

The second stage of photosynthesis can proceed without light, so its steps are sometimes called "light-independent" or "dark" reactions. Many biologists honor the scientist, Melvin Calvin, who won a 1961 Nobel Prize for working out this complex set of chemical reactions, naming it the Calvin Cycle.

The Calvin Cycle has two parts. First carbon dioxide is "fixed." Then ATP and NADPH from the Light Reactions provide energy to combine the fixed carbons to make sugar.

Carbon Dioxide is "Fixed"

Why does carbon dioxide need to be fixed? Was it ever broken?

Life on Earth is carbon-based. Organisms need not only energy but also carbon atoms for building bodies. For nearly all life, the ultimate source of carbon is carbon dioxide (CO_2), an **inorganic molecule**. CO_2, as you saw in **Figure** 4.14, **makes up .038% of the Earth's atmosphere.**

Animals and most other heterotrophs cannot take in CO_2 directly. They must eat other organisms or absorb **organic molecules** to get carbon. Only autotrophs can build low-energy inorganic CO_2 into high-energy **organic molecules** like glucose. This process is **carbon fixation**.

Plants have evolved three pathways for carbon fixation.

The most common pathway combines one molecule of CO_2 with a 5-carbon sugar called ribulose biphosphate (RuBP). The enzyme which catalyzes this reaction (nicknamed **RuBisCo**) is the most abundant enzyme on earth! The resulting 6-carbon molecule is unstable, so it immediately splits into two 3-carbon molecules. The 3 carbons in the first stable molecule of this pathway give this largest group of plants the name "C-3."

Dry air, hot temperatures, and bright sunlight slow the C-3 pathway for carbon fixation. This is because **stomata**, tiny openings under the leaf which normally allow CO_2 to enter and O_2 to leave, must close to prevent loss of water vapor (**Figure** 4.14). Closed stomata lead to a shortage of CO_2. Two alternative pathways for carbon fixation demonstrate biochemical adaptations to differing environments.

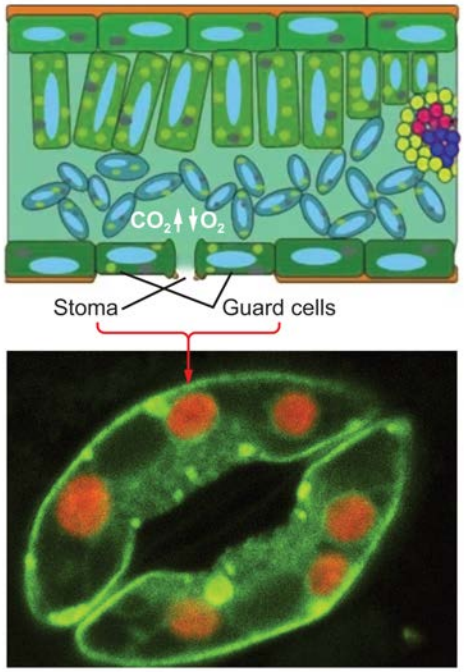


Figure 4.14: Stomata on the underside of leaves take in CO and release water and O. Guard cells close the stomata when water is scarce. Leaf cross-section (above) and stoma (below).

Plants such as corn solve the problem by using a separate compartment to fix CO_2. Here CO_2 combines with a 3-carbon molecule, resulting in a 4-carbon molecule. Because the first stable organic molecule has four carbons, this adaptation has the name C-4. Shuttled away from the initial fixation site, the 4-carbon molecule is actually broken back down into CO_2, and when enough accumulates, Rubisco fixes it a second time! Compartmentalization allows efficient use of low concentrations of carbon dioxide in these specialized plants.

Cacti and succulents such as the jade plant avoid water loss by fixing CO_2 only at night. These plants close their stomata during the day and open them only in the cooler and more humid nighttime hours. Leaf structure differs slightly from that of C-4 plants, but the fixation pathways are similar. The family of plants in which this pathway was discovered gives the pathway its name, Crassulacean Acid Metabolism, or CAM (**Figure** 4.15). All three carbon fixation pathways lead to the Calvin Cycle to build sugar.

How Does the Calvin Cycle Store Energy in Sugar?

As Melvin Calvin discovered, carbon fixation is the first step of a cycle. Like an electron transport chain, the Calvin cycle, shown in **Figure** 4.16, transfers energy in small, controlled steps. Each step pushes molecules uphill in terms of energy content. Recall that in the electron transfer chain, excited electrons lose energy to NADPH and ATP. In the Calvin

Figure 4.15: Even chemical reactions adapt to specific environments! Carbon fixation pathways vary among three groups. Temperate species (maple tree, left) use the C-3 pathway. C-4 species (corn, center) concentrate CO in a separate compartment to lessen water loss in hot bright climates. Desert plants (jade plant, right) fix CO only at night, closing stomata in the daytime to conserve water.

Cycle, NADPH and ATP formed in the light reactions lose their stored chemical energy to build glucose.

Use the diagram below to identify the major aspects of the process:

- the general cycle pattern
- the major reactants
- the products

First, notice where carbon is fixed by the enzyme nicknamed Rubisco. In C-3, C-4, and CAM plants, CO_2 enters the cycle by joining with 5-carbon ribulose bisphosphate to form a 6-carbon intermediate, which splits (so quickly that it isn't even shown!) into two 3-carbon molecules.

Now look for the points at which ATP and NADPH (made in the light reactions) add chemical energy ("Reduction" in the diagram) to the 3-carbon molecules. The resulting "half-sugars" can enter several different metabolic pathways. One recreates the original 5-carbon precursor, completing the cycle. A second combines two of the 3-carbon molecules to form glucose, universal fuel for life.

The cycle begins and ends with the same molecule, but the process combines carbon and energy to build carbohydrates – food for life.

So – how does photosynthesis store energy in sugar? Six "turns" of the Calvin cycle use chemical energy from ATP to combine six carbon atoms from six CO_2 molecules with 12 "hot hydrogens" from NADPH. The result is one molecule of glucose, $C_6H_{12}O_6$.

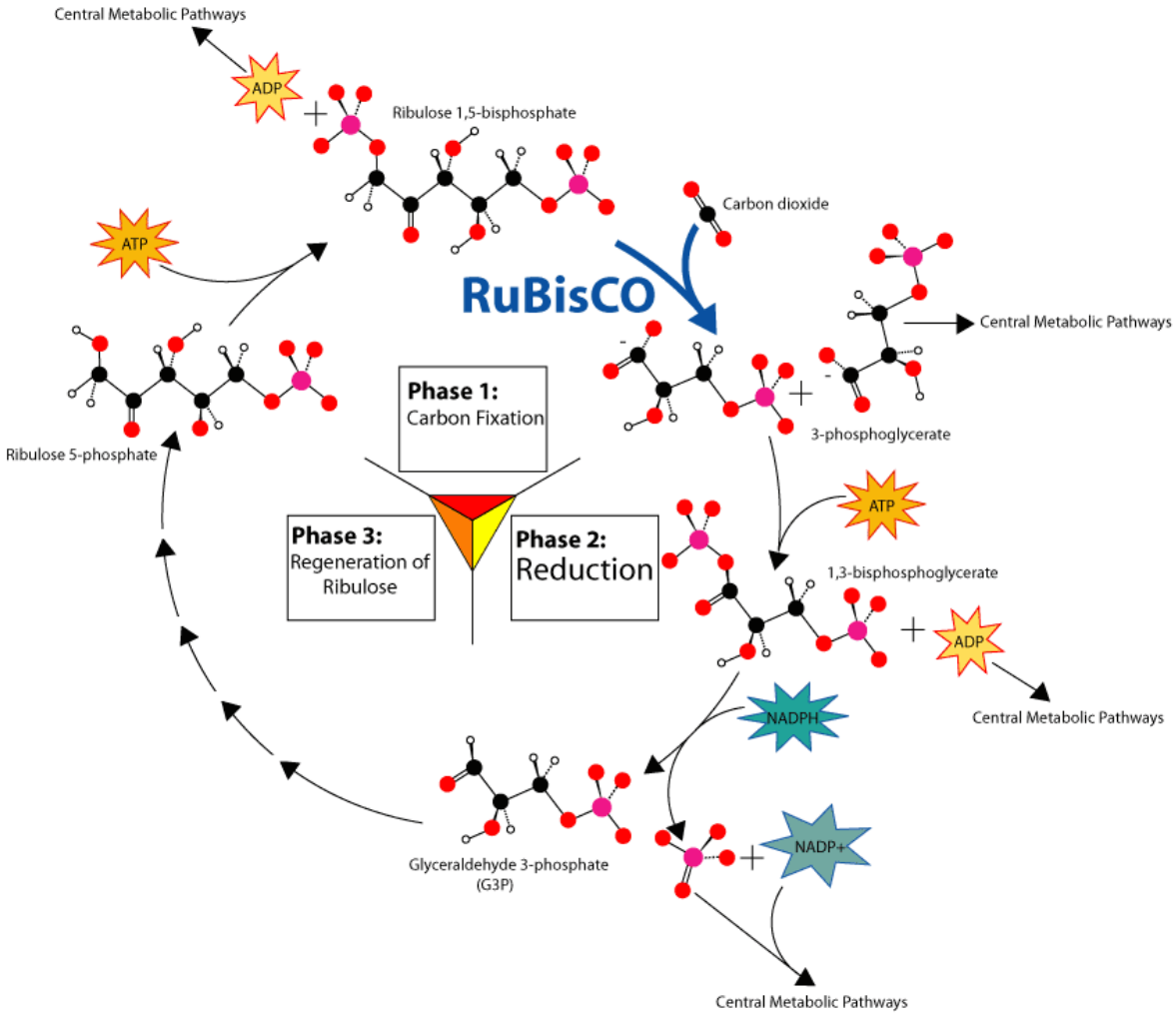
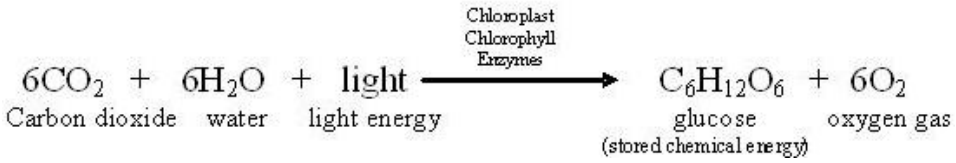


Figure 4.16: Overview of the Calvin Cycle Pathway.

Lesson Summary

The single chemical equation below represents the overall process of photosynthesis as well as summarizes many individual chemical reactions that were understood only after hundreds of years of scientific exploration.



Chloroplasts are the organelles where the process of photosynthesis takes place in plants and algae.

- Chloroplasts resemble blue green bacteria, containing their own DNA and ribosomes.
- The **Endosymbiotic Theory** holds that chloroplasts once were independent prokaryotic cells, but were engulfed by other larger prokaryotes, forming the first eukaryotic cells.
- Chloroplasts are made of membranes, which enclose stacks of membrane sacs called thylakoids.
- The membranes sequence **pigments** and **electron carrier molecules** for efficient photosynthesis.
- **Thylakoids** create compartments, which allow concentration gradients to store energy.
- **Pigment** molecules absorb specific wavelengths (colors) of light; chlorophyll is the primary pigment in photosynthesis.
- **Electron carrier molecules** form **electron transport chains**, which transfer energy in small steps so that the energy can be stored or used for work.

Photosynthesis consists of two groups of chemical reactions: the Light Reactions and the Calvin Cycle.

Light Reactions transform energy from sunlight into chemical energy, and produce and release oxygen gas.

- When light strikes pigment molecules, electrons absorb its energy and are excited.
- Light also provides energy to split water molecules into electrons, hydrogen ions, and oxygen gas.
- The oxygen gas is released as "waste", but it is the source of the oxygen in Earth's atmosphere.
- Two pathways capture the energy from excited electrons as chemical energy stored in the bonds of molecules; both pathways involve **electron transport chains**.
  - One produces **NADPH** molecules, which stores energy and "hot hydrogen".

  - A second pumps hydrogen ions into the thylakoids, forming an electrochemical gradient whose energy builds **ATP** molecules. This is "chemiosmosis".

The Calvin Cycle uses the NADPH and ATP from the Light Reactions to "fix" carbon and produce glucose.

- Stomata underneath plant leaves allow gases (CO_2, H_2O, and O_2) to enter and exit the leaf interior.
- Carbon dioxide enters the Calvin Cycle when an enzyme nicknamed "Rubisco" attaches it to a 5-carbon sugar. The unstable 6-carbon compound immediately breaks into two 3-carbon compounds, which continue the cycle.
- Most plants fix CO_2 directly with this pathway, so they are called C-3 plants.
- Some plants have evolved preliminary fixation pathways, which help them conserve water in hot, dry habitats, but eventually the carbon enters the cycle along the "Rubisco" pathway.
  - C-4 plants such as corn use a 3-carbon carrier to compartmentalize initial carbon fixation in order to concentrate CO_2 before sending it on to Rubisco.
  - CAM plants such as jade plants and some cacti open their stomata for preliminary CO_2 fixation only at night.
- In the Calvin Cycle, the fixed CO_2 moves through a series of chemical reactions, gaining a small amount of energy (or "hot hydrogens") from ATP or NADPH at each step.
- Six turns of the cycle process 6 molecules of carbon dioxide and 12 "hot hydrogens" to produce a single molecule of glucose.
- The cycle begins and ends with the same 5-carbon molecule, but the process stores chemical energy in food for nearly all life.

Summary Animations

- These interactive web sites depicts each step of photosynthesis in great detail.

http://www.johnkyrk.com/photosynthesis.html
http://www.johnkyrk.com/photosynthesisdark.html

Review Questions

1. Summarize Jan Van Helmont's willow tree experiment. State his conclusion and the inference he made after his experiment, and explain how his data supports each. Finally, relate his findings to what we know today about the overall process of photosynthesis.
2. Using the overall equation for photosynthesis, explain which components relate to J.B. Priestley's observation that "Plants restore the air that animals injure."

3. Explain how the structure of a chloroplast – its membranes and thylakoids – makes its function – the chemical reactions of photosynthesis – more efficient.
4. Summarize the Endosymbiotic Theory. What evidence related to chloroplasts supports this theory?
5. Name the two stages (sets of reactions) which make up the process of photosynthesis.
6. Match the major events with the stage of photosynthesis in which they occur. **Stages**Light Reactions
   Calvin Cycle
   Major Events

   (a) Carbon dioxide is fixed.
   (b) Electrons in chlorophyll jump to higher energy levels.
   (c) Glucose is produced.
   (d) NADPH and ATP are produced.
   (e) NADPH and ATP are used.
   (f) Oxygen gas is released.
   (g) Water is split.

7. Use your understanding of pigments to explain why the living world appears green. Then think a little further and offer a hypothesis to explain why the world is not black!
8. Explain the value of cycles of chemical reactions, such as the Calvin Cycle.
9. Explain how their various methods of carbon fixation adapt C-3, C-4, and CAM plants to different habitats.
10. We humans depend on photosynthesis, and our actions in turn affect photosynthesis. Explain how humans depend on photosynthesis for:

    (a) food
    (b) building materials for furniture and homes
    (c) fuel for vehicles, heat, and electricity
    (d) breathable air

    Explain how the following actions would affect photosynthesis:

    (a) We may clear-cut a forest for timber and parking lot space
    (b) When we burn fossil fuels for transportation or heat, we release CO2 into the atmosphere
    (c) When we dam up and overuse water in a certain area, the area water table drops

Further Reading / Supplemental Links

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- Laurence A. Moran and Pearson Prentice Hall, "Fixing Carbon: The Rubisco reaction," 10 July 2007. Sandwalk: Strolling with a Skeptical Biochemist,
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- http://vcell.ndsu.nodak.edu/animations/photosynthesis/index.htm.

Vocabulary

accessory pigment A molecule which absorbs colors of light other than blue-violet and red, and then transfers the energy to chlorophyll.

ATP synthase Ion channel and enzyme complex that chemically bonds a phosphate group to ADP, making ATP as H^+ ions flow through the ion channel.

Calvin Cycle The second stage of photosynthesis, which can proceed without light, so its steps are sometimes called "light-independent" or "dark" reactions; results in the formation of a sugar.

carbon fixation The process which converts carbon dioxide in the air to organic molecules, as in photosynthesis.

chlorophyll The primary pigment of photosynthesis.

chloroplast The organelle in plant and algal cells where photosynthesis takes place.

electron carrier A molecule which transfers energy-carrying electrons within an electron transport chain.

electron transport chain (ETC) A series of electron-carrying molecules which accept and pass along energy-carrying electrons in small steps, allowing the energy lost at each transfer to be captured for storage or work.

endosymbiotic theory The theory which states that chloroplasts and mitochondria originated as independent prokaryotic cells which were engulfed by larger prokaryotic cells to form the first eukaryotic cells.

glucose The carbohydrate product of photosynthesis; serves as the universal fuel for life.

light-dependent reactions The first set of reactions of photosynthesis; requires sunlight; also called the light reactions.

NADPH An energy carrier molecule produced in the light reactions of photosynthesis; used to build sugar in the Calvin cycle.

photolysis The light reaction process of splitting water molecules into electrons, hydrogen ions, and oxygen gas.

photosynthesis The process by which plants, algae, and some bacteria transform sunlight into chemical energy and use it to produce carbohydrate food and oxygen for almost all life.

photosystem A cluster of proteins and pigments found in chloroplasts and active in photosynthesis.

pigment A molecule which absorbs specific wavelengths of light energy and reflects others and therefore appears colored.

RuBisCo The enzyme that combines one molecule of CO_2 with a 5-carbon sugar called ribulose biphosphate (RuBP); the most abundant enzyme on earth.

stomata (singular stoma) Openings on the underside of a leaf which allow gas exchange and transpiration.

thylakoid Flattened sac-shaped compartment within a chloroplast, made of membranes embedded with molecules which carry out photosynthesis.

Points to Consider

- Recall Priestley's early observation that plants "restore the air." Name some ways that plants and algae affect the atmosphere.
- Which of your own activities affect photosynthesis? Think "globally" in addition to "locally" and add large-scale human activities to your list. Are there any changes you could make in your life which could promote photosynthesis and a healthy atmosphere?
- You learned in this chapter that plants make "food" which life needs for energy. But is it usable energy? Or does it need to be converted into some other type of energy? What do you think and why?

Image Sources

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(2) CK-12 Foundation. http://en.wikipedia.org/wiki/Image:Par_action_spectrum.gif. CC-BY-SA 2.0.

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Chapter 5

Cellular Respiration

5.1 Lesson 5.1: Powering the Cell: Cellular Respiration and Glycolysis

Lesson Objectives

- Clarify the relationship between breathing and cellular respiration.
- Trace the flow of energy from food molecules through ATP to its use in cellular work.
- Compare cellular respiration to burning.
- Analyze the chemical equation for cellular respiration.
- Briefly describe the role of mitochondria in producing ATP.
- Compare cellular respiration to photosynthesis.
- Show how carbon and oxygen atoms cycle through producers, consumers, and the environment.
- Recognize that glycolysis is the first and most universal of three stages in cellular respiration.
- Explain why biologists consider glycolysis to be one of the oldest energy production pathways.
- Describe how some of the energy in glucose is transferred to ATP in the cytoplasm, without oxygen.

Introduction

You know that humans deprived of oxygen for more than a few minutes will quickly become unconscious and die. Breathing, also known as respiration, is essential for human life, because the body cannot store oxygen for later use as it does food. The mammalian respiratory system, shown in **Figure** 5.1 features a diaphragm, trachea, and a thin membrane whose

surface area is equivalent to the size of a handball court - all for efficient oxygen intake. Other forms of life employ different types of respiratory organs: fish and aquatic amphibians and insects flaunt gills, spiders and scorpions develop "book lungs," and terrestrial insects use an elaborate network of tubes called tracheae, which open via spiracles, as shown in **Figure** 5.2 and **Figure** 5.3. A constant supply of oxygen gas is clearly important to life. However, do you know why you need oxygen?

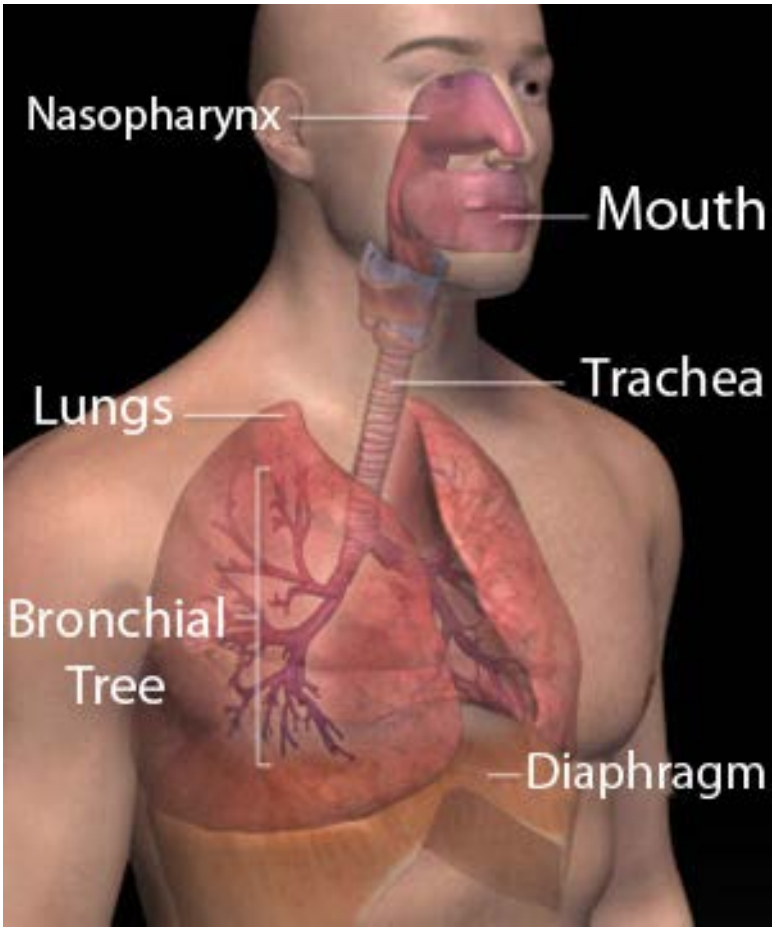


Figure 5.1: The human respiratory system is only part of the story of respiration. Diaphragm, lungs, and trachea take air deep into the body and provide oxygen gas to the bloodstream. The fate of that oxygen is the story of cellular respiration.

Many people would answer that oxygen is needed to make carbon dioxide, the gas exhaled or released by each of the respiratory systems listed above. However, CO_2 is waste product. Surely, there is more to the story than just gas exchange with the environment! To begin to appreciate the role of oxygen inside your body, think about when your breathing rate increases: climbing a steep slope, running a race, or skating a shift in a hockey game. Respiration rate correlates with energy use, and that correlation reflects the link between oxygen and energy metabolism. For this reason, the chemical reactions inside your cells that

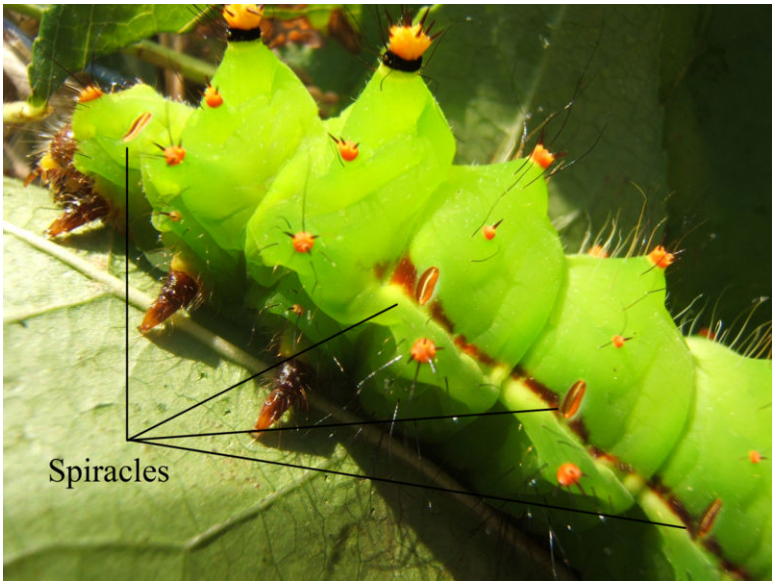


Figure 5.2: Spiracles in this Indian Luna Moth () caterpillar connect to a system of internal tubes (tracheae) which carry oxygen throughout the animal's body.

Figure 5.3: Gills in this alpine newt larva, , bring blood close to an extensive surface area so that the newt can absorb dissolved oxygen gas from its watery habitat.

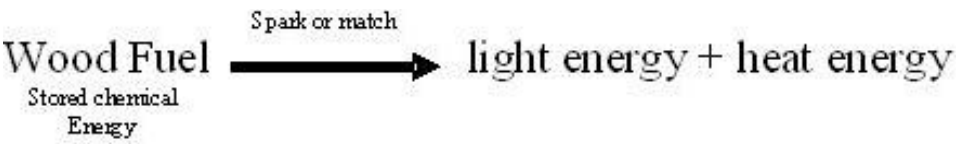
consume oxygen to produce usable energy are known as **cellular respiration**. This chapter will introduce you to the overall process of cellular respiration, and then focus on the first stage, which by itself does not require oxygen.

An Overview of Cellular Respiration

Another way to think about the role of oxygen in your body - and a good starting point for understanding the whole process of cellular respiration - is to recall the last time you sat by a campfire (see below figure) and noticed that it was "dying." Often people will blow on a campfire to keep it from "dying out." How does blowing help? What happens in a campfire?

Figure 5.4: Analyzing what happens when wood burns in a campfire is a good way to begin to understand cellular respiration.

You know that a fire produces light and heat energy. However, it cannot "create" energy (remember that energy cannot be created or destroyed). Fire merely transforms the energy stored in its fuel – chemical energy – into light and heat. Another way to describe this energy transformation is to say that burning releases the energy stored in fuel. As energy is transformed, so are the compounds that make up the fuel. In other words, burning is a chemical reaction. We could write our understanding of this energy-releasing chemical reaction up to this point as:



Now return to what happens when you blow on a fire. The fire was "dying out," so you blew on it to get it going again. Was it movement or something in the air that promoted the chemical reaction? If you have ever "smothered" a fire, you know that a fire needs something in the air to keep burning. That something turns out to be oxygen. Oxygen gas is a reactant in the burning process. At this point, our equation is:

$$O_2 + \underset{\text{Stored chemical Energy}}{\text{Wood Fuel}} \xrightarrow{\text{Spark or match}} \text{light energy} + \text{heat energy}$$

To complete this equation, we need to know what happens to matter, to the atoms of oxygen, and to the atoms of the fuel during the burning. If you collect the gas rising above a piece of burning wood in an inverted test tube, you will notice condensation - droplets appearing on the sides of the tube. Cobalt chloride paper will change from blue to pink, confirming that these droplets are water. If you add bromothymol blue (BTB) to a second tube of collected gases, the blue solution will change to green or yellow (**Figure** 5.5), indicating the presence of carbon dioxide. Thus, carbon dioxide and water are products of burning wood.

Figure 5.5: Bromothymol blue (BTB) changes from blue to green to yellow as carbon dioxide is added. Thus, it is a good indicator for this product of burning or cellular respiration.

$$O_2 + \underset{\text{Stored chemical Energy}}{\text{Wood Fuel}} \xrightarrow{\text{Spark or match}} CO_2 + H_2O + \text{light energy} + \text{heat energy}$$

Now we know what happened to those oxygen atoms during the chemical reaction, but we need to be sure to identify the sources of the carbon atoms in the CO_2 and of the hydrogen atoms in the water. If you guessed that these atoms make up the wood fuel – and nearly all fuels we burn, from coal to propane to candle wax to gasoline (hydrocarbons!), you have solved the equation completely. Overall, burning is the combining of oxygen with hydrogen and carbon atoms in a fuel (combustion or oxidation) to release the stored chemical energy as heat and light. Products of combustion are CO_2 (oxidized carbon) and H_2O (oxidized hydrogen). Or in symbols,

$$O_2 + \underset{\text{Stored chemical Energy}}{C_x\text{-}H_y} \xrightarrow{\text{Spark or match}} CO_2 + H_2O + \text{light energy} + \text{heat energy}$$

Return to the fate of the oxygen gas you breathe in and absorb. Recall that we related breathing rate and oxygen intake to energy use. Burning consumes oxygen as it releases stored chemical energy, transforming it into light and heat. Cellular respiration is actually a slow burn. Your cells absorb the oxygen carried by your blood from your lungs, and use the O_2 to release stored chemical energy so that you can use it.

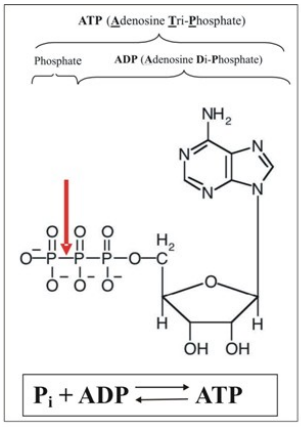
However, releasing energy within cells does not produce light or intense heat. Cells run on chemical energy – specifically, the small amount temporarily stored in adenine triphosphate (ATP) molecules. Cellular respiration transfers chemical energy from a "deliverable" fuel molecule – **glucose** – to many "usable" molecules of **ATP**. Like oxygen, glucose is delivered by your blood to your cells. If ATP were delivered to cells, more than 60,221,417,930,000,000,000,000,000 of these large molecules (which contain relatively small amounts of energy) would clog your capillaries each day. Pumping them across cell membranes would "cost" a great deal of energy. A molecule of glucose contains a larger amount of chemical energy in a smaller package. Therefore, glucose is much more convenient for bloodstream delivery, but too "powerful" to work within the cell. The process of cellular respiration uses oxygen to help transfer the chemical energy from glucose to ATP, which can be used to do work in the cell. This chemical equation expresses what we have worked out:

$$O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} \longrightarrow \underset{\text{stored chemical energy, usable}}{ATP}$$

As with burning, we must trace what happens to atoms during cellular respiration. You can readily see that when the carbon atoms in glucose are combined with oxygen, they again form carbon dioxide. And when the hydrogen atoms in glucose are oxidized, they form water, as in burning. You can detect these products of cellular respiration in your breath on a cold day (as water condensation) and in the lab (BTB turns yellow when you blow into it through a straw). The equation:

$$O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} \longrightarrow \underbrace{ATP}_{\text{stored chemical energy, usable}} + CO_2 + H_2O$$

This accounts for the energy transfer and the carbon, hydrogen, and oxygen atoms, but it does not show the "raw materials" or reactants which build ATP. Recall that the energy temporarily stored in ATP is released for use when the bond between the second and third phosphates is broken. The resulting ADP can be recycled within the cell by recombining it with inorganic phosphate (P_i).



Now you should be able to see that the source of energy for re-attaching the phosphate is the chemical energy in glucose! Materials cycle and recycle, but energy gets used up and must be replaced. That is the key to understanding cellular respiration: it is a "recharging of the batteries" - ATP molecules – which power cellular work. How many ATP can be made by harnessing the energy in a single glucose molecule? Although this number varies under certain conditions, most cells can capture enough energy from one molecule of glucose to build 38 molecules of ATP. Our equation becomes:

$$O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} + 38ADP + 38P_i \longrightarrow \underbrace{38\ ATP}_{\text{stored chemical energy, usable}} + CO_2 + H_2O$$

This equation for cellular respiration is not quite complete, however, because we can easily mix air and glucose sugar (even adding ADP and P_i) and nothing will happen. For the campfire, we indicated above the arrow that a necessary condition was a spark or match to start the reaction. A spark or match would damage or destroy living tissue. What necessary condition initiates the slow burn that is cellular respiration? Recall that enzymes are highly specific proteins which "speed up" chemical reactions in living cells. More than 20 kinds of enzymes carry out cellular respiration! If you also recall that membranes within organelles often sequence enzymes for efficiency, as in chloroplasts for photosynthesis, you will not be surprised that a specific organelle, the **mitochondrion** (**Figure** 5.6), is also a necessary condition of cellular respiration - at least in eukaryotes.

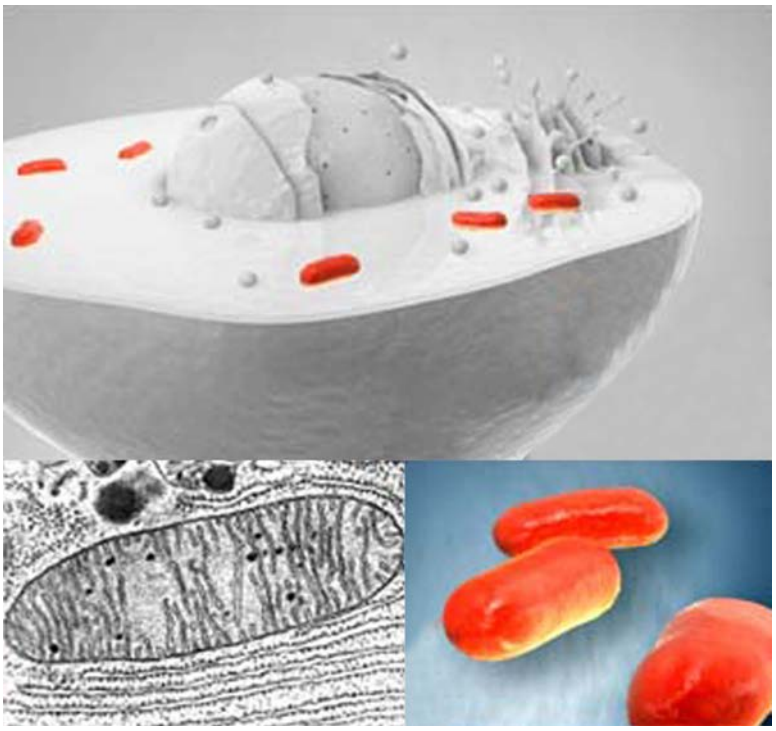


Figure 5.6: Mitochondria are membranous organelles which sequence enzyme and electron carrier molecules to make cellular respiration highly efficient.

Within each eukaryotic cell, the membranes of 1000-2000 mitochondria sequence enzymes and electron carriers and compartmentalize ions so that cellular respiration proceeds efficiently. Mitochondria, like chloroplasts, contain their own DNA and ribosomes and resemble certain bacteria. The endosymbiotic theory holds that mitochondria, too, were once independently living prokaryotes. Larger prokaryotes engulfed (or enslaved) these smaller aerobic cells, forming eukaryotic cells. Many prokaryotes today can perform cellular respiration; perhaps they and mitochondria have common ancestors. Their expertise in generating ATP made mitochondria highly valued symbionts.

Including these necessary conditions and balancing numbers of atoms on both sides of the arrow, our final equation for the overall process of cellular respiration is:

$$6O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

In words, cellular respiration uses oxygen gas to break apart the carbon-hydrogen bonds in glucose and release their energy to build 38 molecules of ATP. Most of this process occurs within the mitochondria of the cell. Carbon dioxide and water are waste products. This is similar to burning, in which oxygen breaks the carbon-hydrogen bonds in a fuel and releases their chemical energy as heat and light. Again, carbon dioxide and water are waste.

If you have studied the process of photosynthesis, you've probably already noticed its similarity to the process of cellular respiration. Both are processes within the cell which make chemical energy available for life. Photosynthesis transforms light energy into chemical energy stored in glucose, and cellular respiration releases the energy from glucose to build ATP, which does the work of life. Moreover, photosynthesis reactants CO_2 and H_2O are products of cellular respiration. And the reactants of respiration, $C_6H_{12}O_6$ and O_2, are the products of photosynthesis. This interdependence is the basis of the carbon-oxygen cycle (**Figure** 5.7), which connects producers to consumers and their environment. At first glance, the cycle merely seems to show mitochondria undoing what chloroplasts do; but the cycle's energy transformations power all the diversity, beauty, and mystery of life.

An excellent animation demonstrating cellular respiration can be found at the following web site:

- http://videos.howstuffworks.com/hsw/10323-matter-and-energy-glycolysis-and-cellular
htm

Glycolysis: A Universal and Ancient Pathway for Making ATP

When was the last time you enjoyed yogurt on your breakfast cereal, or had a tetanus shot? These experiences may appear unconnected, but both relate to bacteria which do not use

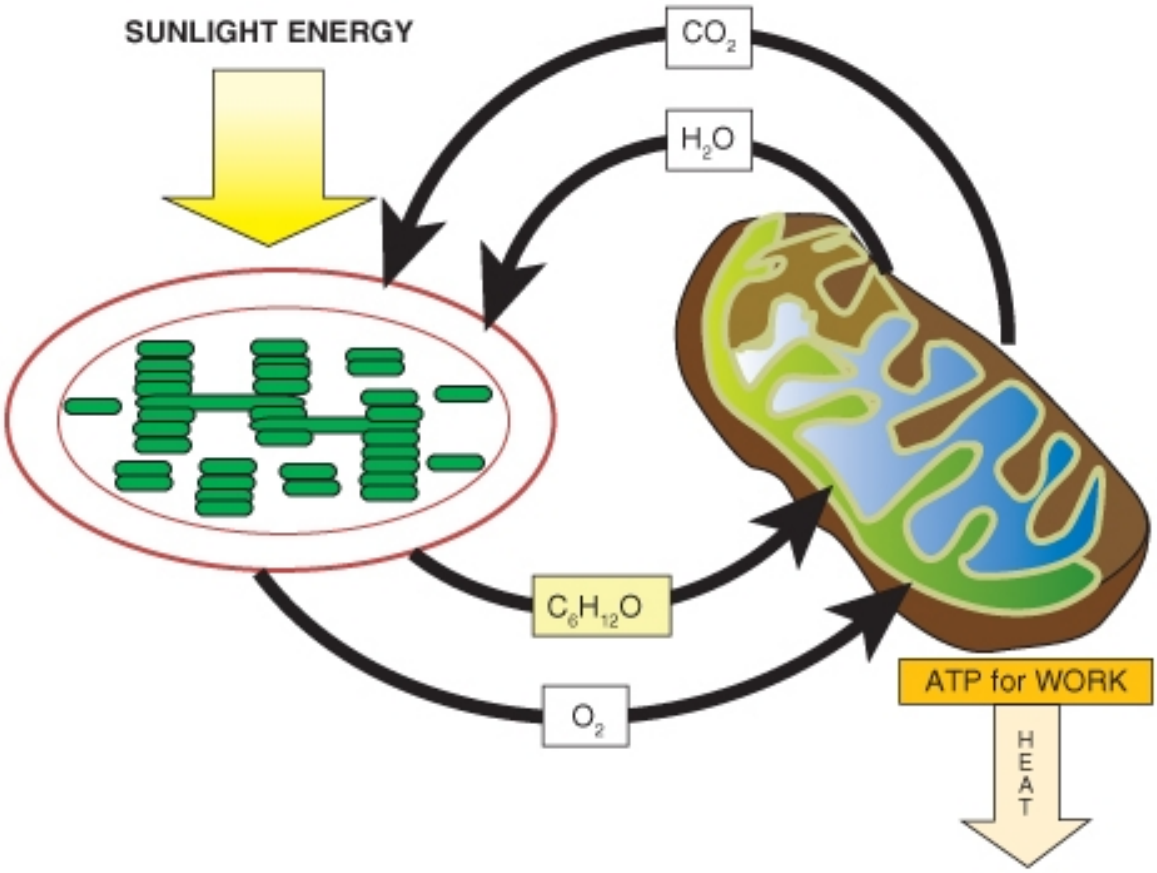


Figure 5.7: Photosynthesis in the chloroplast and cellular respiration in the mitochondrion show the interdependence of producers and consumers, the flow of energy from sunlight to heat, and the cycling of carbon and oxygen between living world and environment.

oxygen to make ATP. In fact, tetanus bacteria cannot survive if oxygen is present. However, *Lactobacillus acidophilus* (bacteria which make yogurt) and *Clostridium tetani* (bacteria which cause tetanus or lockjaw) share with nearly all organisms the first stage of cellular respiration, glycolysis (**Figure** 5.8). Because glycolysis is universal, whereas aerobic (oxygen-requiring) cellular respiration is not, most biologists consider it to be the most fundamental and primitive pathway for making ATP.

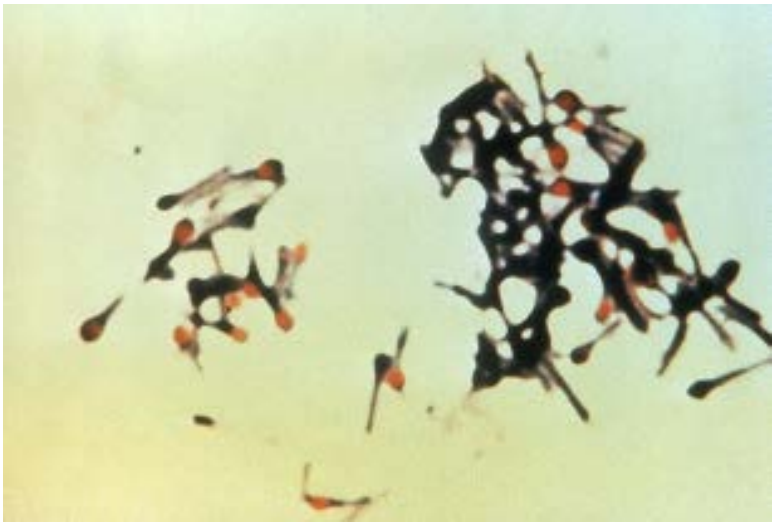


Figure 5.8: bacteria are obligate anaerobes, which cannot grow in the presence of oxygen and use a variation of glycolysis to make ATP. Because they can grow in deep puncture wounds and secrete a toxin, which can cause muscle spasms, seizures, and death, most people receive tetanus vaccinations at least every ten years throughout life.

Return to the overall equation for cellular respiration:

$$6O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} 38ATP + 6CO_2 + 6H_2O \quad \underset{\text{stored chemical energy, usable}}{}$$

Like photosynthesis, the process represented by this equation is actually many small, individual chemical reactions. We grouped the reactions of photosynthesis into two stages, the light reactions and the Calvin Cycle. We will divide the reactions of cellular respiration into three stages: glycolysis, the Krebs Cycle, and the electron transport chain (**Figure** 5.9). In this section, we will explore Stage 1, glycolysis - the oldest and most widespread pathway for making ATP. Before diving into the details, we must note that this first stage of cellular respiration is unique among the three stages: it does not require oxygen, and it does not take place in the mitochondrion. The chemical reactions of glycolysis occur without oxygen in the **cytosol** of the cell (**Figure** 5.10).

The name for Stage 1 clearly indicates what happens during that stage: *glyco-* refers to glucose, and *-lysis* means "splitting." In glycolysis, within the cytosol of the cell, a minimum of eight different enzymes break apart glucose into two 3-carbon molecules. The energy

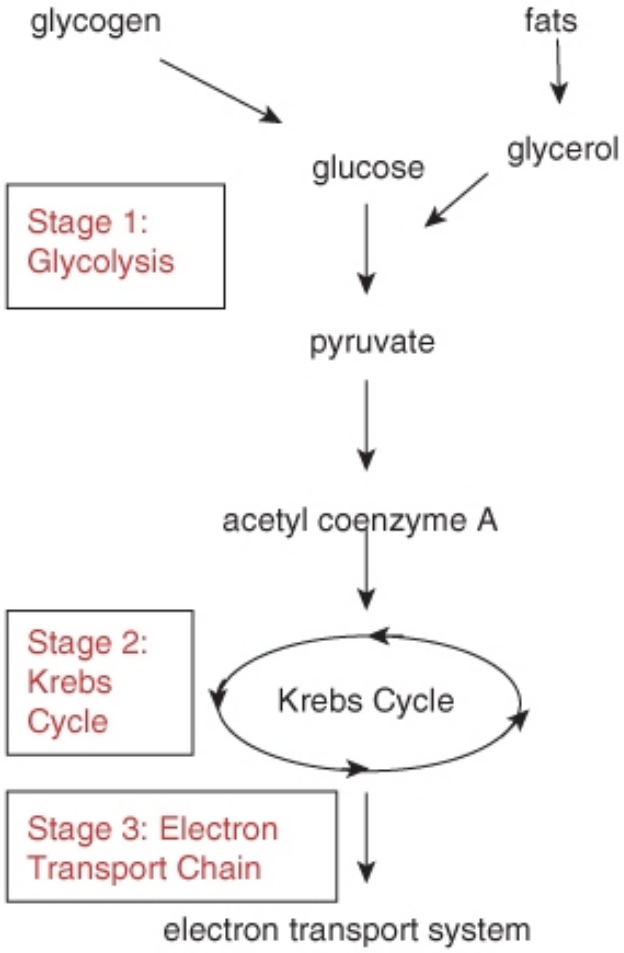


Figure 5.9: The many steps in the process of aerobic cellular respiration can be divided into three stages. The first stage, glycolysis, produces ATP without oxygen. Because this part of the cellular respiration pathway is universal, biologists consider it the oldest segment. Note that and fats can also enter the glycolysis pathway.

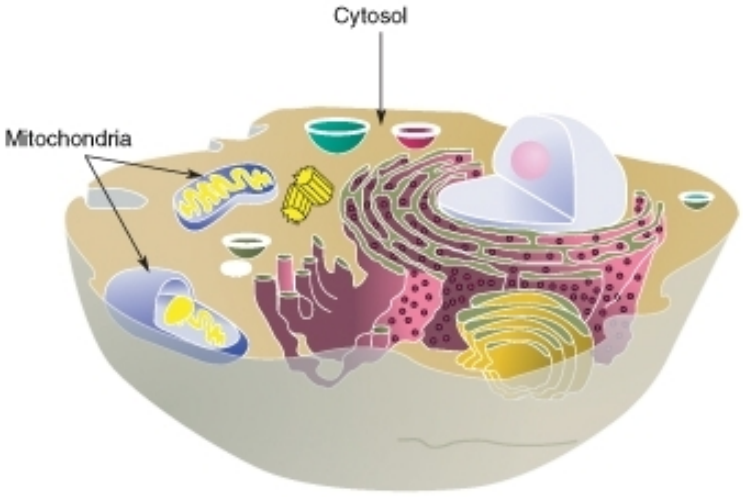


Figure 5.10: Glycolysis, unlike the latter two stages of cellular respiration, takes place without oxygen in the cytosol of the cell. For many organisms, aerobic respiration continues with the Krebs cycle and the electron transport chain in the mitochondria.

released in breaking those bonds is transferred to carrier molecules, ATP and NADH. **NADH** temporarily holds small amounts of energy which can be used later to build ATP. The 3-carbon product of glycolysis is pyruvate, or pyruvic acid (**Figure** 5.11). Overall, glycolysis can be represented as shown below:

$$C_6H_{12}O_6 + 2NAD^+ + 2P_i + 2ADP \rightarrow 2\ \text{pyruvate} + 2NADH + 2ATP$$

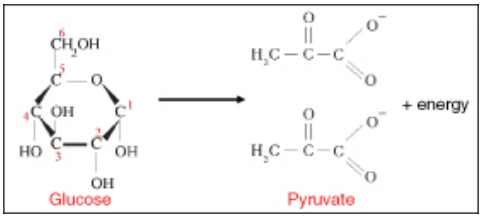


Figure 5.11: Glycolysis breaks the 6-carbon molecule glucose into two 3-carbon pyruvate molecules, releasing some of the chemical energy which had been stored in glucose.

However, even this equation is deceiving. Just the splitting of glucose requires many steps, each transferring or capturing small amounts of energy. Individual steps appear in **Figure** 5.12. Studying the pathway in detail reveals that cells must "spend" or "invest" two ATP in order to begin the process of breaking glucose apart. Note that the phosphates produced by breaking apart ATP join with glucose, making it unstable and more likely to break apart. Later steps harness the energy released when glucose splits, and use it to build "hot hydrogens" (NAD^+ is reduced to NADH) and ATP (ADP + P_i $\longrightarrow$ ATP). If you count the

ATP produced, you will find a net yield of two ATP per glucose (4 produced – 2 spent). Remember to double the second set of reactions to account for the two 3-carbon molecules which follow that pathway! The "hot hydrogens" can power other metabolic pathways, or in many organisms, provide energy for further ATP synthesis.

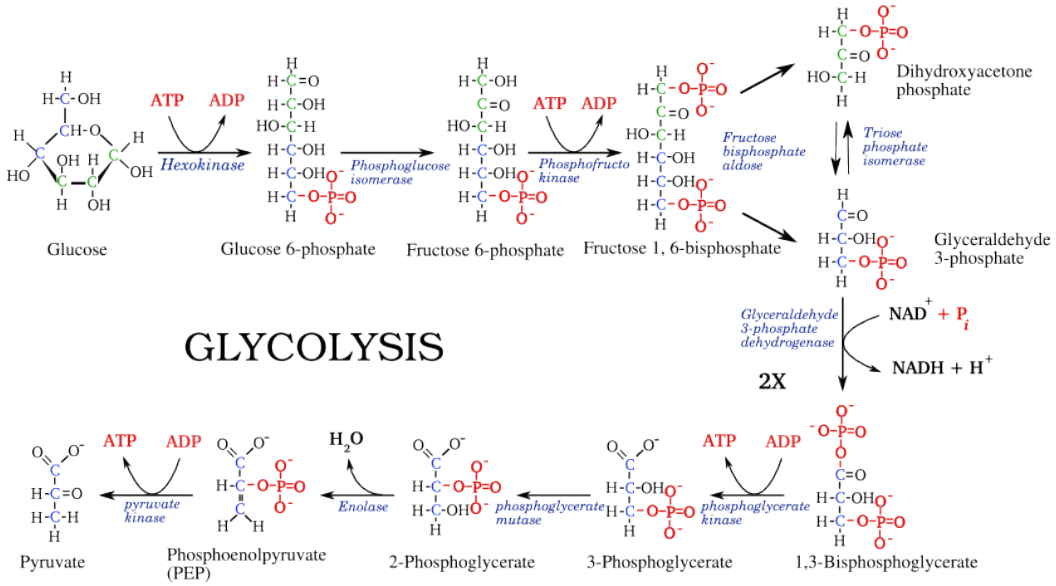


Figure 5.12: This detailed diagram demonstrates that glycolysis "costs" 2 ATP, but harnesses enough energy from breaking bonds in glucose to produce 4 ATP and 2 pairs of "hot hydrogens" (NADH + H). Note the multiplier (2X) required for the 3-carbon steps.

To summarize: In the cytosol of the cell, glycolysis transfers some of the chemical energy stored in one molecule of glucose to two molecules of ATP and two NADH. This makes (some of) the energy in glucose, a universal fuel molecule for cells, available to use in cellular work - moving organelles, transporting molecules across membranes, or building large organic molecules.

Although glycolysis is universal, pathways leading away from glycolysis vary among species depending on the availability of oxygen. If oxygen is unavailable, pyruvate may be converted

to lactic acid or ethanol and carbon dioxide in order to regenerate NAD^+, ending anaerobic respiration. **Anaerobic** respiration is also called fermentation, which we will discuss in a later section.

If oxygen is present, pyruvate enters the mitochondria for further breakdown, releasing far more energy and producing many more molecules of ATP in the latter two stages of aerobic respiration - the Krebs cycle and electron transport chain. We will explore these, too, in a later section.

Lesson Summary

- Most organisms need oxygen for a single purpose: to release energy from food for use by cells.
- Cellular respiration is a series of chemical reactions which transfer energy from glucose (deliverable or fuel energy) to ATP (usable energy).
- Analyzing a campfire can clarify your understanding of cellular respiration. A campfire breaks chemical bonds in wood, releasing stored energy as light and heat; respiration breaks chemical bonds in glucose, releasing stored energy and transferring some to 38 ATP; some energy is lost as heat.
- This equation summarizes the process of cellular respiration:

$$6O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} + 38ADP + 38P_i \xrightarrow{\text{enzymes, mitochondria}} \underbrace{38ATP}_{\text{stored chemical energy, usable}} + 6CO_2 + 6H_2O$$

- In eukaryotic cells, organelles called mitochondria sequence enzymes and electron carriers and compartmentalize ions so that cellular respiration proceeds efficiently.
- Cellular respiration, in many ways the opposite of photosynthesis, shows the interdependence of producers and consumers. Combined, the two equations demonstrate how energy flows and the carbon and oxygen cycle between organisms and environment.
- The process of cellular respiration is actually many separate reactions, which can be divided into three stages: glycolysis, the Krebs Cycle, and the electron transport chain.

Review Questions

1. Why do nearly all organisms die without a constant supply of oxygen?
2. What source of energy do cells use to build ATP by cellular respiration?
3. Compare the purpose and energy content of glucose to the function and energy content of ATP; in other words, why do organisms need both kinds of energy-rich molecules?
4. Compare the process of burning gasoline in your automobile's engine to the process of cellular respiration in terms of reactants, products, and necessary conditions.

5. Write out the chemical reaction which summarizes the overall process of cellular respiration, first in symbols as a chemical equation, and then in words in a complete sentence.
6. In what eukaryote organelle does cellular respiration take place? Does this mean that prokaryotes cannot carry out the entire process of cellular respiration? Explain.
7. Compare and contrast cellular respiration and photosynthesis.
8. Diagram the carbon-oxygen cycle which connects producers, consumers, and their environment. (P = producer, C = consumer).
9. List the three stages of cellular respiration, and contrast the first stage with the other two in terms of distribution throughout the living world, location within the cell, and use of oxygen.
10. Summarize the overall process of glycolysis, following both carbon atoms and chemical energy.

Further Reading / Supplemental Links

- Martin Hoagland, Bert Dodson, and Judith Hauck, *Exploring the Way Life Works: The Science of Biology.* Jones and Bartlett Publishers, Inc., 2001. Chapter 3: "Energy – Light to Life," pp. 87-138.
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Vocabulary

aerobic With oxygen, or living or occurring only in the presence of oxygen.

anaerobic Without oxygen; living or occurring in the absence of oxygen.

ATP Adenosine triphosphate; the universal energy "currency" for the cell; molecule which stores a usable amount of chemical energy.

cellular respiration The process which transfers chemical energy from glucose (a deliverable fuel molecule) to ATP (a usable energy-rich molecule).

cytosol The solution portion of a cell's cytoplasm, consisting of water, organic molecules and ions.

endosymbiotic theory The theory which states that chloroplasts and mitochondria originated as independent prokaryotic cells which were engulfed by larger prokaryotic cells to form the first eukaryotic cells.

glucose The carbohydrate product of photosynthesis; serves as the universal fuel for life.

glycogen Glucose molecules that have been chained together for energy storage; human muscle and liver cells store energy in this form.

glycolysis The process of splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

mitochondrion The "powerhouse" organelle in all eukaryotic cells where stages 2 (Krebs Cycle) and 3 (Electron Transport Chain) of aerobic respiration produce ATP.

NADH An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

symbiont An organism which lives in a close, mutually beneficial relationship with another organism.

Points to Consider

- In this lesson, you've learned that scientists consider glycolysis to be the oldest, or at least one of the oldest, pathways for making ATP. What might this say about earth's ancient atmosphere? Can you imagine steps or events that might have been involved in the later evolution of aerobic cellular respiration, which includes glycolysis?
- Prokaryotes can use either photosynthesis or cellular respiration – or both - to make ATP. Why do you think both processes evolved? Why not just photosynthesis? Which do you think came first in evolution? Why?
- This lesson compares cellular respiration to burning. What activities in your daily life use burning? What are some consequences of those activities, in terms of materials produced and energy used?

5.2 Lesson 5.2: Into the Mitochondrion: Making ATP with Oxygen

Lesson Objectives

- Relate the history of oxygen in the atmosphere to the evolution of photosynthesis, aerobic respiration, mitochondria, and life on earth.
- Describe the fate in eukaryotic cells of the pyruvate molecules produced by glycolysis if oxygen is present.
- Recognize that for most organisms, if oxygen is present, the products of glycolysis enter the mitochondria for stage 2 of cellular respiration - the Krebs Cycle.
- Trace carbon and hydrogen atoms through the Krebs Cycle.
- Analyze the importance of the Krebs Cycle to cellular respiration by following the pathway taken by chemical energy.
- Describe the structure of the mitochondrion, and identify the site of Krebs Cycle reactions.
- Recognize that electron transport chain is the third and final stage of aerobic cellular respiration.
- Describe how chemiosmotic gradients in mitochondria store energy to produce ATP.
- Identify the role of oxygen in making stored chemical-bond energy available to cells.
- Relate the structure of mitochondria to electron transport chain function and the production of ATP.

Introduction

Enticing clues - volcanic gases, vast iron ore sediments, and bubbles of ancient air trapped in amber – suggest dramatic changes during the history of earth's atmosphere. Correlating these clues with the fossil record leads to two major conclusions: that early life evolved in the absence of oxygen, and that oxygen first appeared between 2 and 3 billion years ago (**Figure** 5.13) because of photosynthesis by bluegreen bacteria (**Figure** 5.14). The chemistry of cellular respiration reflects this history. Its first stage, **glycolysis**, is universal and does not use oxygen.

Absolutely dependent on oxygen gas, we find it difficult to imagine that its appearance must have been disastrous for the anaerobic organisms that evolved in its absence. But oxygen is highly reactive, and at first, its effect on evolution was so negative that some have named this period the "oxygen catastrophe." However, as oxygen gradually formed a protective ozone layer, life rebounded. After the first organisms "discovered" how to use oxygen to their advantage – in ways we will explore in this chapter – the diversity of aerobic organisms exploded. According to the **endosymbiotic theory**, engulfing of some of these aerobic bacteria led to eukaryotic cells with mitochondria, and multicellularity followed. Today, we live in an atmosphere which is 21% oxygen, and most of life follows glycolysis with the last

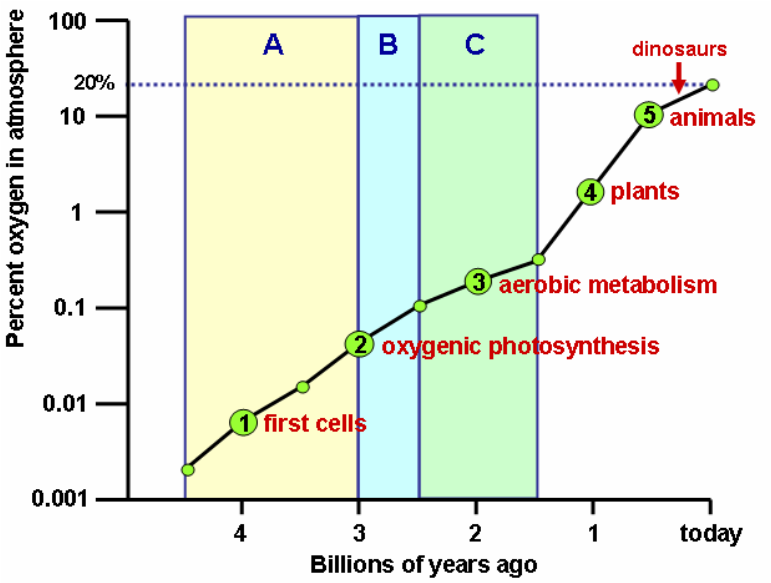

Figure 5.13: Oxygen has increased in the atmosphere throughout the history of the earth. Note the logarithmic scale, which indicates great increases after first photosynthesis and then land plants evolved. Related geological events: A = no oxidized iron; B = oxidized iron bands in seabed rock - evidence for O in the oceans; C= oxidized iron bands on land and ozone layer formation- evidence for O in the atmosphere.

Figure 5.14: Bubbles of oxygen appear at the surface above a mat of bluegreen bacteria in a freshwater pond. Studies of the fossil record and earth's atmosphere suggest that life evolved before bacteria similar to these first added oxygen.

two, aerobic stages of cellular respiration.

Recall the purpose of cellular respiration: to release energy from glucose to make **ATP** - the universal "currency" for cellular work. The following equation describes the overall process, although it summarizes many individual chemical reactions.

$$6O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

Once again, the first stage of this process, glycolysis, is ancient, universal, and anaerobic. In the cytoplasm of most cells, glycolysis breaks each 6-carbon molecule of glucose into two 3-carbon molecules of pyruvate. Chemical energy, which had been stored in the now broken bonds, is transferred to 2 ATP and 2 "hot hydrogens," **NADH**.

The fate of pyruvate depends on the species and the presence or absence of oxygen. If oxygen is present to drive subsequent reactions, pruvate enters the mitochondrion, where the **Krebs Cycle** (Stage 2) and electron transport chain (Stage 3) break it down and oxidize it completely to CO_2 and H_2O. The energy thus released builds many more ATP molecules, though of course some is lost as heat. Let's explore the details of how mitochondria use oxygen to make more ATP from glucose by aerobic respiration.

The Krebs Cycle: Capturing Energy from Pyruvate

Aerobic respiration begins with the entry of pyruvate (product of glycolysis) into the mitochondria. We will follow the six carbons of the original glucose molecule, so we will consider two 3-carbon pyruvates. The fate of pyruvate's energy and carbon atoms can be followed in the examples below:

1. Within the mitochondria, each pyruvate is broken apart and combined with a coenzyme known as CoA to form a 2-carbon molecule, Acetyl CoA, which can enter the Krebs Cycle. A single atom of carbon (per pyruvate) is "lost" as carbon dioxide. The energy released in this breakdown is captured in two "hot hydrogen" – NADH. See **Figure** 5.15. Fatty acids can also break down into Acetyl CoA. By this means, lipids, like carbohydrates, can be "burned" to make ATP using the Krebs Cycle.
2. The Krebs Cycle (**Figure** 5.16) begins by combining each Acetyl CoA with a four-carbon carrier molecule to make a 6-carbon molecule of citric acid (or citrate, its ionized form). For this reason, the Krebs Cycle, named for a scientist who worked out its details, is also called the Citric Acid Cycle.
3. The cycle carries citric acid through a series of chemical reactions which gradually release energy and capture it in several carrier molecules. For each Acetyl CoA which enters the cycle, 3 NAD+ are reduced to NADH, one molecule of FAD (yet another temporary energy carrier we haven't met before) is reduced to $FADH_2$, and one molecule

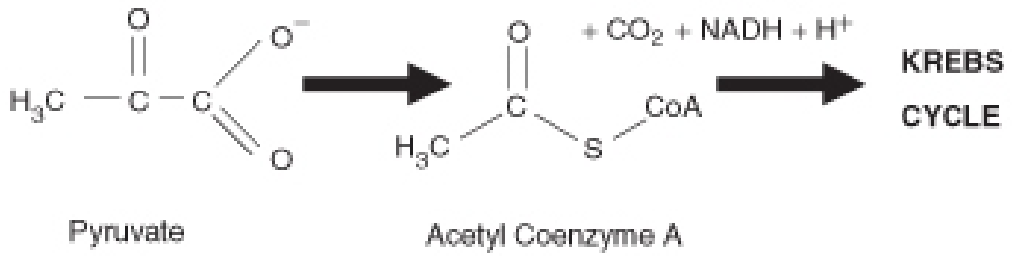

Figure 5.15: After glycolysis, two 3-carbon pyruvates enter the mitochondrion, where they are converted to two 2-carbon acetyl CoenzymeA (CoA) molecules. Acetyl CoA then enters the Krebs Cycle. Note that the carbons removed become carbon dioxide, accounting for two of the six such end products of glucose oxidation. The energy released by this breakdown is carried by "hot hydrogen."

of ATP (actually a precursor, GTP) is made. Study **Figure** 5.16 to locate each of these energy-capturing events.

4. Note what happens to carbon atoms (black dots in **Figure** 5.16). For each 2-carbon Acetyl CoA which enters the cycle, two molecules of carbon dioxide are released - complete breakdown of the original 6-carbon glucose molecule. The final step regenerates the original 4-carbon molecule which began the cycle, so that another Acetyl CoA can enter.

In summary, the Krebs Cycle completes the breakdown of glucose which began with glycolysis. Its chemical reactions oxidize all six of the original carbon atoms to CO_2, and capture the energy released in 2 ATP, 6 NADH, and 2 $FADH_2$. These energy carriers join the 2 ATP and 2 NADH produced in glycolysis and the 2 NADH produced in the conversion of 2 pyruvates to 2 Acetyl CoA.

At the conclusion of the Krebs Cycle, glucose is completely broken down, yet only four ATP have been produced. Moreover, although oxygen is required to drive the Krebs Cycle, the cycle's chemical reactions do not themselves consume O_2. The conclusion of cellular respiration – its "grand finale!" – produces the majority of the ATP. The next section will explore the electron transport chain, where Stage 3 concludes aerobic cellular respiration.

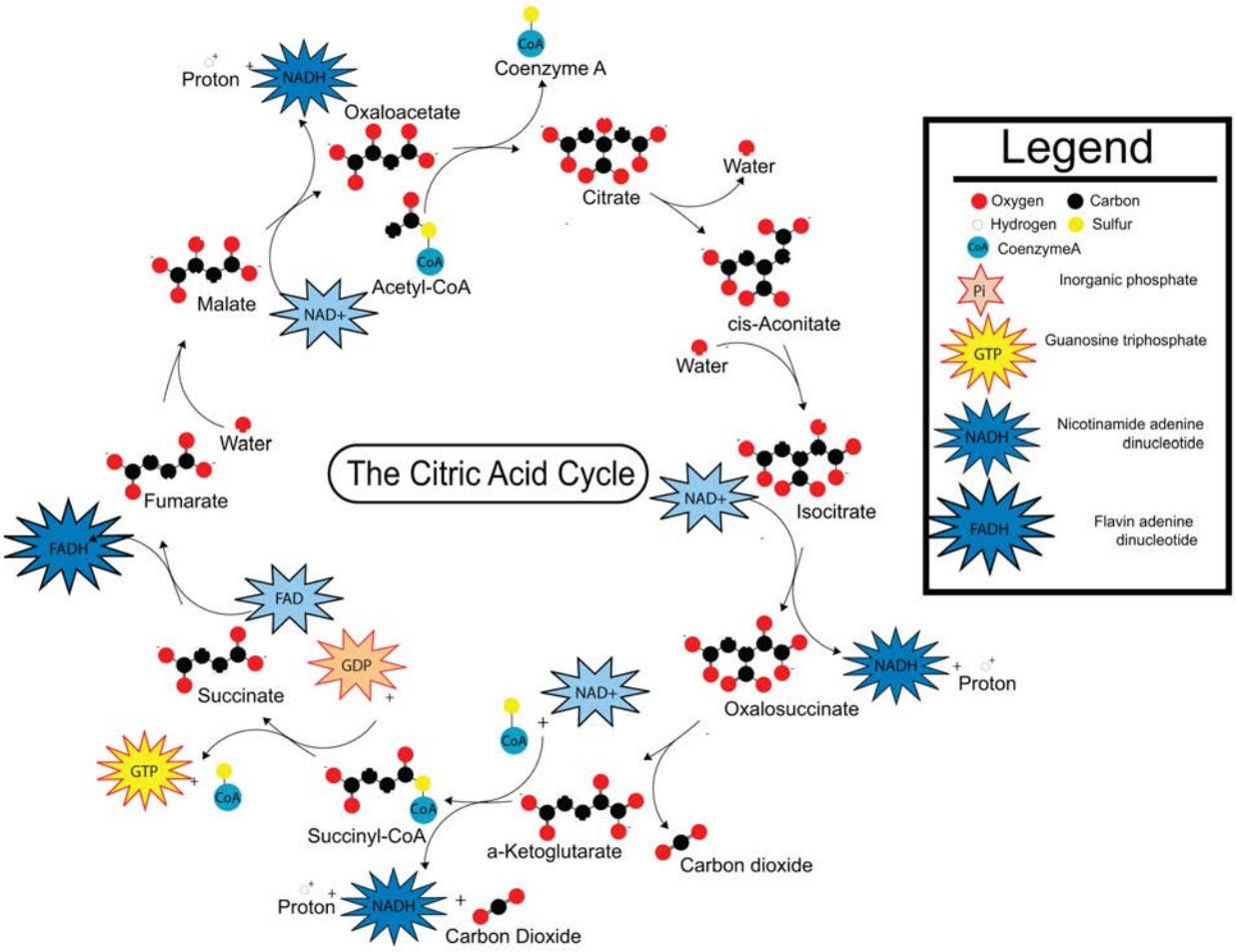

Figure 5.16: The Krebs or Citric Acid Cycle completes the breakdown of glucose begun in glycolysis. If oxygen is present, pyruvate enters the mitochondria and is converted to Acetyl CoA. Acetyl CoA enters the cycle by combining with 4-carbon oxaloacetate. Study the diagram to confirm that each turn of the cycle (two for each glucose) stores energy in 3 NADH+H, one FADH, and one ATP (from GTP), and releases 2 CO.

Structure of the Mitochondrion: Key to Aerobic Respiration

As noted earlier, the aerobic phases of cellular respiration in eukaryotes occur within organelles called mitochondria. A detailed look at the structure of the **mitochondrion** (**Figure** 5.17) helps to explain its role in the last stage of respiration, the electron transport chain.

Two separate membranes form the mitochondrion. The inner membrane folds into **cristae** which divide the organelle into three compartments – **intermembrane space** (between outer and inner membranes), cristae space (formed by infoldings of the inner membrane), and matrix (within the inner membrane). The Krebs Cycle takes place within the matrix. The compartments are critical for the electron transport chain, as we'll see in the final section of this lesson. Glycolysis occurs in the cytoplasm of the cell, with the products of glycolysis entering the mitochondria to continue cellular respiration.

The Electron Transport Chain: ATP for Life in the Fast Lane

At the end of the Krebs Cycle, energy from the chemical bonds of glucose is stored in diverse energy carrier molecules: four ATP, but also two **$FADH_2$** and ten NADH. The primary task of the last stage of cellular respiration, the electron transport chain (ETC), is to transfer energy from these carriers to ATP, the "batteries" which power work within the cell.

Pathways for making ATP in stage 3 of aerobic respiration closely resemble the electron transport chains used in photosynthesis. In both ETCs, energy carrier molecules are arranged in sequence within a membrane so that energy-carrying electrons cascade from one to another, losing a little energy in each step. In both photosynthesis and aerobic respiration, the energy lost is harnessed to pump hydrogen ions into a compartment, creating an **electrochemical** or **chemiosmotic gradient** across the enclosing membrane. And in both processes, the energy stored in the chemiosmotic gradient is used to build ATP.

For aerobic respiration, the **electron transport chain** or "respiratory chain" is embedded in the inner membrane of the mitochondria (**Figure** 5.18). $FADH_2$ and NADH (produced in glycolysis and the Krebs Cycle) donate high-energy electrons to energy carrier molecules within the membrane. As they pass from one carrier to another, the energy they lose is used to pump hydrogen ions into the intermembrane space, creating an electrochemical gradient. Hydrogen ions flow "down" the gradient – from outer to inner compartment – through an ion channel/enzyme, **ATP synthase,** which transfer their energy to ATP. Note the paradox that it requires energy to create and maintain a concentration gradient of hydrogen ions that are then used by ATP synthase to create stored energy (ATP). In broad terms, it takes energy to make energy. Coupling the electron transport chain to ATP synthesis with a hydrogen ion gradient is chemiosmosis, first described by Nobel laureate Peter D. Mitchell.

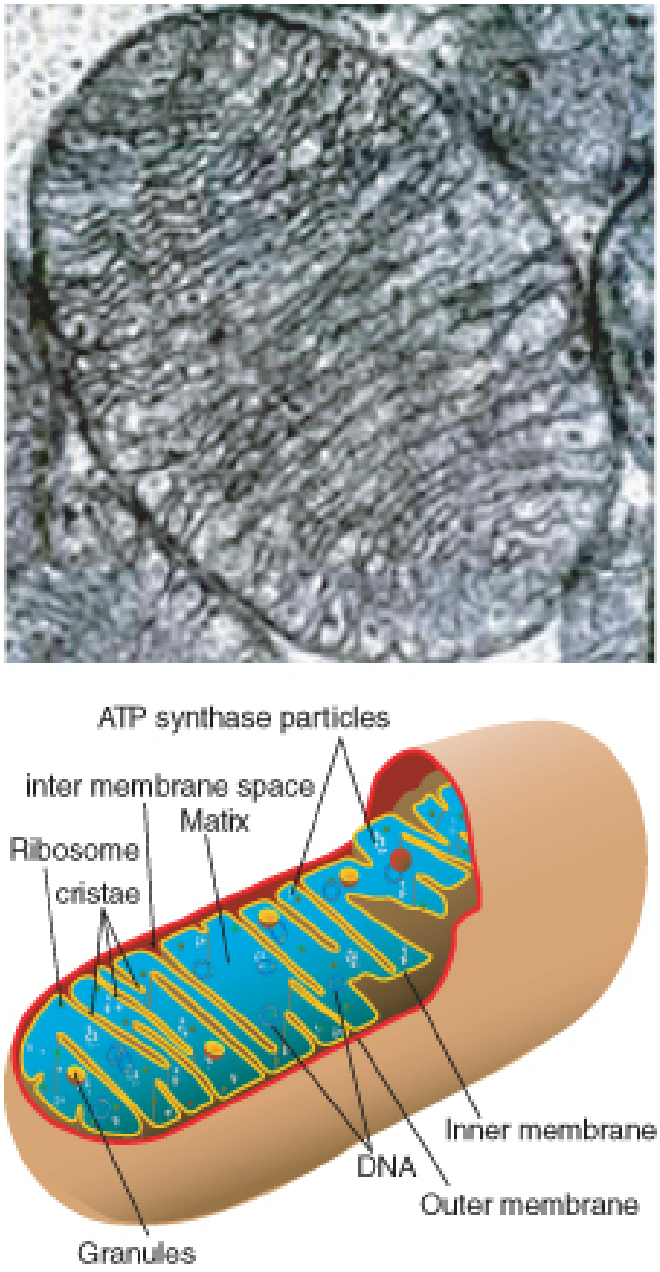

Figure 5.17: Mitochondria, organelles specialized to carry out aerobic respiration, contain an inner membrane folded into cristae, which form two separate kinds of compartments: inner membrane space and matrix. The Krebs Cycle takes place in the . The electron transport chain is embedded in the inner membrane and uses both compartments to make ATP by .

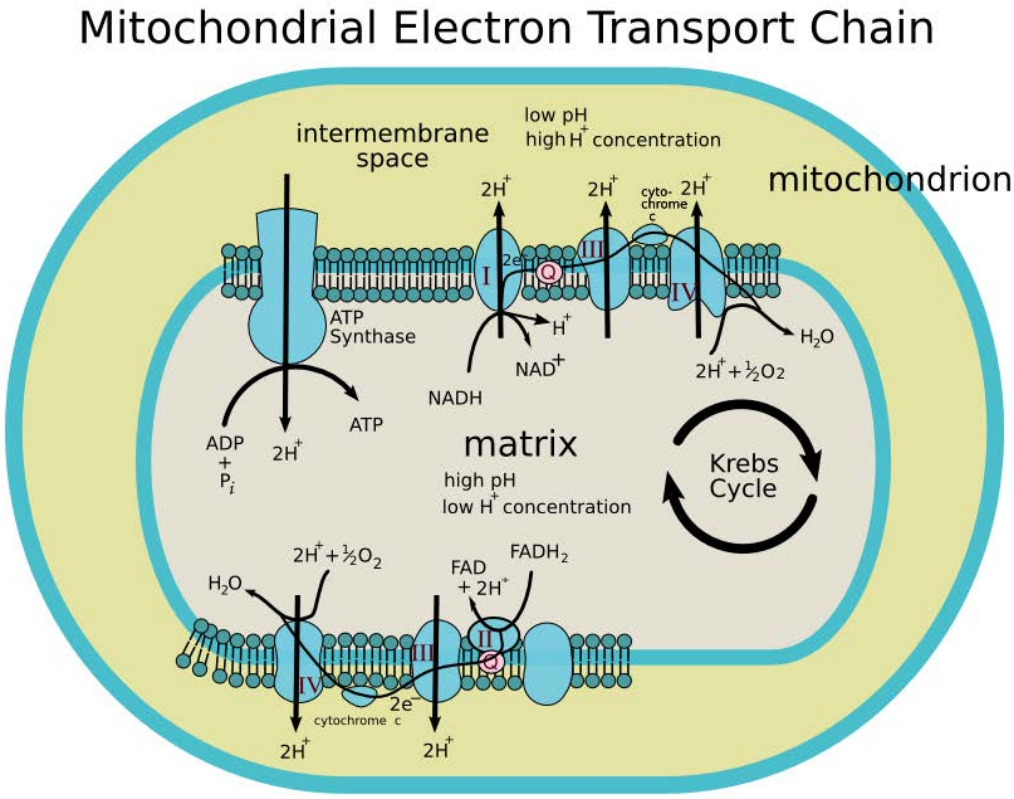

Figure 5.18: The third stage of photosynthesis uses the energy stored earlier in NADH and FADH to make ATP. Electron transport chains embedded in the inner membrane capture high-energy electrons from the carrier molecules and use them to concentrate hydrogen ions in the intermembrane space. Hydrogen ions flow down their electrochemical gradient back into the matrix through channels which capture their energy to convert ADP to ATP.

After passing through the ETC, low-energy electrons and low-energy hydrogen ions combine with oxygen to form water. Thus, oxygen's role is to drive the entire set of ATP-producing reactions within the mitochondrion by accepting "spent" hydrogens. Oxygen is the final electron acceptor; no part of the process - from the Krebs Cycle through electron transport chain – can happen without oxygen.

The electron transport chain can convert the energy from one glucose molecule's worth of $FADH_2$ and $NADH+H^+$ into as many as 34 ATP. When the four ATP produced in glycolysis and the Krebs Cycle are added, the total fits the overall equation for aerobic cellular respiration:

$$\underset{\text{stored chemical energy, deliverable}}{6O_2 + C_6H_{12}O_6} + 38ADP + 38P_i \longrightarrow \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

Aerobic respiration is complete. If oxygen is available, cellular respiration transfers the energy from one molecule of glucose to 38 molecules of ATP, releasing carbon dioxide and water as waste. "Deliverable" food energy has become energy which can be used for work within the cell – transport within the cell, pumping ions and molecules across membranes, and building large organic molecules. Can you see how this could lead to "life in the fast lane" compared to anaerobic respiration (glycolysis alone)?

Lesson Summary

Introduction to Aerobic Respiration:

- Oxygen produced by the first photosynthetic organisms was probably toxic to the anaerobic life forms which then populated the earth, but later organisms evolved a way to harness the power of oxygen to make ATP. This new pathway was aerobic respiration.
- In eukaryotic cells, if oxygen is present, the pyruvate molecules produced by glycolysis in the cytoplasm enter the mitochondria for further breakdown and energy release.

The Krebs Cycle harnesses the energy which remains in pyruvate after glycolysis.

- For most organisms, if oxygen is present, the products of glycolysis enter the mitochondria for stage 2 of cellular respiration - the Krebs cycle.
- In the mitochondrion, 3-carbon pyruvate combines with Coenzyme A to form 2-carbon Acetyl CoA and CO_2, storing released energy in NADH.
- Acetyl CoA enters the Krebs Cycle by combining with a 4-carbon molecule to form citric acid.
- The Krebs Cycle removes energy from citric acid in small steps, storing it in diverse energy carrier molecules: ATP, NADH and $FADH_2$.

- The Krebs Cycle produces two molecules of CO_2 per Acetyl CoA, completing the breakdown of glucose.

Mitochondria are organelles whose membranes are specialized for aerobic respiration.

- The matrix of the mitochondria is the site of Krebs Cycle reactions.
- The electron transport chain and most ATP synthesis rely on the compartments created by the inner membrane of the mitochondria.

The third and final stage of aerobic cellular respiration, the electron transport chain, accounts for most of the ATP.

- Stage 3 transfers the energy from NADH and $FADH_2$ to make ATP.
- High-energy electrons from these two energy carriers pass along electron acceptors embedded in the inner membrane of the mitochondria.
- As the electrons flow, the electron acceptors capture small amounts of energy to pump hydrogen ions out into the intermembrane space.
- These concentrated hydrogen ions store potential energy as an electrochemical gradient.
- Hydrogen ions flow back into the inner membrane space through channel proteins, which use their energy to build ATP. This is chemiosmosis.
- The ETC coupled with the hydrogen ion flow can build 34 ATP per glucose molecule.
- When ATP from glycolysis and the Krebs Cycle are added, a total of 38 ATP result from aerobic respiration of one molecule of glucose.

Summary Animations

- Interactive animation depicting the steps of cellular respiration.

http://www.uwmc.uwc.edu/biology/respiration/cellresp.html

- Animation detailing the steps of electron transport chain.

http://vcell.ndsu.edu/animations/etc/movie-flash.htm

- Animation detailing the H^+ concentration gradient and ATP Synthase.

http://vcell.ndsu.edu/animations/atpgradient/movie-flash.htm

Review Questions

1. Explain why the appearance of oxygen in the atmosphere between two and three billions of years ago was both "good news and bad news" for life on Earth.
2. In eukaryotic cells when oxygen is present, what is the fate of the pyruvate produced in glycolysis?
3. Trace the six carbon atoms originally from glucose through the Krebs Cycle.
4. Trace the flow of energy from the pyruvates produced in glycolysis through the Krebs Cycle.
5. Describe the structure of the mitochondrion, and identify the sites of the Krebs Cycle and the Electron Transport Chain.
6. Summarize the overall task of Stage 3 of aerobic respiration.
7. List the steps in stage 3 which produce ATP.
8. Name the three stages of aerobic cellular respiration. Then write the overall equation, and identify which stage:
    - uses each reactant
    - requires each necessary condition and
    - produces each product.
9. Explain the principle of chemiosmosis.
10. Predict the main idea of the next lesson by comparing the energy available to anaerobic organisms, which use just glycolysis to make ATP, to the energy available to aerobic organisms, which use all three stages of cellular respiration to make ATP.

Further Reading / Supplemental Links

- Martin Hoagland, Bert Dodson, and Judith Hauck, *Exploring the Way Life Works: The Science of Biology.* ones and Bartlett Publishers, Inc., 2001. Chapter 3: "Energy – Light to Life," pp. 87-138.
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- http://www.pitt.edu/AFShome/j/b/jbrodsky/public/html/1820/tca.htm

Vocabulary

ATP Adenosine triphosphate; the universal energy "currency" for the cell; molecule which stores a usable amount of chemical energy.

ATP synthase Ion channel and enzyme complex that chemically bonds a phosphate group to ADP, making ATP as H^+ ions flow through the ion channel.

chemiosmosis Process in cellular respiration or photosynthesis which produces ATP using the energy of hydrogen ions diffusing from high concentration to low.

chemiosmotic gradient In cellular respiration or photosynthesis, a difference in concentration of hydrogen ions across a membrane within the mitochondrion or chloroplast set up using energy from an electron transport chain.

cristae The space formed by infoldings of the inner membrane within the mitochondrian.

electrochemical gradient A difference in both electrical charge and chemical concentration across a membrane.

electron transport chain (ETC) A series of electron-carrying molecules which accept and pass along energy-carrying electrons in small steps, allowing the energy lost at each transfer to be captured for storage or work.

endosymbiotic theory The theory which states that chloroplasts and mitochondria originated as independent prokaryotic cells which were engulfed by larger prokaryotic cells to form the first eukaryotic cells.

$FADH_2$ An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

glycolysis The process of "splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

Krebs Cycle Stage 2 of aerobic cellular respiration; a series of chemical reactions which completes the breakdown of glucose begun in stage 1, releasing more chemical energy and producing carbon dioxide; also called the Citric Acid Cycle.

intermembrane space The space between the outer and inner membranes of the mitochondrian.

matrix The space within the inner membrane of the mitochondrian.

mitochondrion The "powerhouse" organelle in all eukaryotic cells where stages 2 (Krebs Cycle) and 3 (Electron Transport Chain) of aerobic respiration produce ATP.

NADH An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

Points to Consider

- According to the endosymbiotic theory, although some prokaryotes evolved aerobic respiration, eukaryotes took the short-cut of engulfing these prokaryotes rather than "re-inventing the wheel." The benefits to the "host" cells are obvious. What might have been some of the benefits to the prokaryote?
- Cycles, electron transport chains, and chemiosmosis are common to both photosynthesis and cellular respiration. Why do you think they're found in both energy pathways?

5.3 Lesson 5.3: Anaerobic Respiration: ATP, New Fuels, and Yogurt without Oxygen

Lesson Objectives

- Distinguish between obligate aerobes, obligate anaerobes, and facultative anaerobes.
- Explain that, in the absence of oxygen fermentation reactions must regenerate NAD+ in order for glycolysis to continue making ATP.
- Discuss how your muscles continue to work for you even when your respiratory and cardiovascular system can no longer keep up a continuous supply of oxygen.

- Identify yourself as "sprinter" or "endurance runner" and predict the type of muscle fiber (red or white) which predominates in your body.
- Describe how bacteria, including those we employ to make yogurt, make ATP in the absence of oxygen.
- Compare and contrast alcoholic and lactic acid fermentation pathways.
- Outline the process used to produce fuel from corn.
- Explain how we employ anaerobic organisms to make bread, beer, and wine.
- Compare the energy efficiency of aerobic cellular respiration to that of fermentation.
- List the advantages of anaerobic over aerobic respiration.
- Explain why vertebrate muscles use both aerobic and anaerobic pathways to make ATP.

Introduction

After the photosynthetic "oxygen catastrophe" challenged life between 2.5 and 3 billion years ago, evolution rebounded with biochemical pathways to harness and protect against oxygen's power. Today, most organisms use O_2 in aerobic respiration to produce ATP. Almost all animals, most fungi, and some bacteria are **obligate aerobes**, which require oxygen. Some plants and fungi and many bacteria retain the ability to make ATP without oxygen. These **facultative anaerobes** use ancient anaerobic pathways when oxygen is limited. A few bacteria remain as **obligate anaerobes**, which die in the presence of oxygen and depend on only the first (anaerobic) stage of cellular respiration.

Aerobic and anaerobic pathways diverge after glycolysis splits glucose into two molecules of pyruvate:

$$C_6H_{12}O_6 + 2NAD^+ + 2P_i + 2ADP \rightarrow 2\,\text{pyruvate} + 2NADH + 2ATP$$

Pyruvate still contains a great deal of chemical energy. If oxygen is present, pyruvate enters the mitochondria for complete breakdown by the Krebs Cycle and electron transport chain. If oxygen is not present, cells must transform pyruvate to regenerate NAD+ in order to continue making ATP. Two different pathways accomplish this with rather famous products: lactic acid and ethyl alcohol (**Figure** 5.19). Making ATP in the absence of oxygen by glycolysis alone is known as fermentation. Therefore, these two pathways are called **lactic acid fermentation** and **alcoholic fermentation**. If you lack interest in organisms, such as yeast and bacteria, which have "stuck with" the anaerobic tradition, the products of these chemical reactions may still intrigue you. Fermentation makes bread, yogurt, beer, wine, and some new biofuels. In addition, some of your body's cells are facultative anaerobes, retaining one of these ancient pathways for short-term, emergency use.

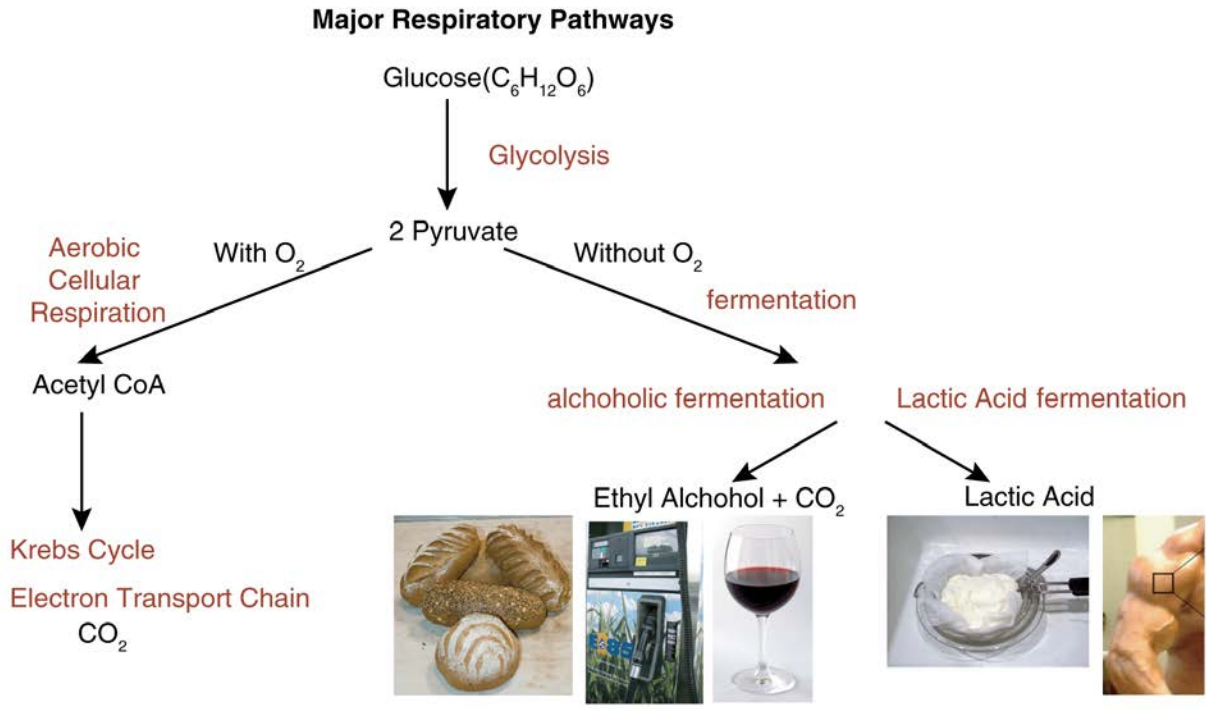


Figure 5.19: Anaerobic and aerobic respiration share the glycolysis pathway. If oxygen is not present, fermentation may take place, producing lactic acid or ethyl alcohol and carbon dioxide. Products of fermentation still contain chemical energy, and are used widely to make foods and fuels.

Lactic Acid Fermentation: Muscle Cells and Yogurt

For chicken or turkey dinners, do you prefer light meat or dark? Do you consider yourself a sprinter, or a distance runner? (**Figure** 5.20)

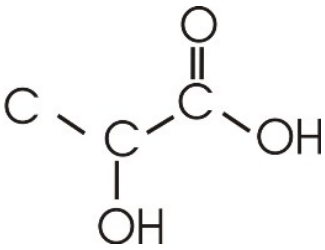
Figure 5.20: Light meat or dark? Sprinting or endurance? Muscle cells know two ways of making ATP – aerobic and anaerobic respiration.

Are Drumsticks and Athletic Prowess Related?

Yes! Muscle color reflects its specialization for aerobic or anaerobic metabolism. Although humans are obligate aerobes, our muscle cells have not given up on ancient pathways which allow them to keep producing ATP quickly when oxygen runs low. The difference is more pronounced in chickens and grouse (**Figure** 5.21), which stand around all day on their legs. For long periods of time, they carry out aerobic respiration in their "specialized-for-endurance" red muscles. If you have ever hunted grouse, you know that these birds "flush" with great speed over short distances. Such "sprinting" flight depends on anaerobic respiration in the white cells of breast and wing muscle. No human muscle is all red or all white, but chances are, if you excel at running short distances or at weight lifting, you have more white glycolytic fibers in your leg muscles. If you run marathons, you probably have more red oxidative fibers.

You probably were not aware that muscle cells "ferment." **Lactic acid fermentation** is the type of anaerobic respiration carried out by yogurt bacteria (*Lactobacillus* and others) and by your own muscle cells when you work them hard and fast. Converting pyruvate to 3-carbon lactic acid (see **Figure** below) regenerates NAD+ so that glycolysis can continue to make ATP in low-oxygen conditions.

Figure 5.21: Ruffed grouse use anaerobic respiration (lactic acid fermentation) in wing and breast muscles for quick bursts of speed to escape from predators (and hunters!).



$C_3H_3O_3$ (pyruvate) + NADH $\rightarrow$ $C_3H_6O_3$ (lactic acid) + NAD^+

For *Lactobacillus*bacteria, the acid resulting from fermentation kills bacterial competitors in buttermilk, yogurt, and some cottage cheese. The benefits extend to humans who enjoy these foods, as well (**Figure** 5.22).

You may have noticed this type of fermentation in your own muscles, because muscle fatigue and pain are associated with lactic acid. Keep this in mind, however, as we discuss a second type of fermentation, which produces alcohol. Imagine what would happen as you ran a race if muscle cells conducted alcoholic rather than lactic acid fermentation!

Alcoholic Fermentation: A "New" Source of Energy?

Have you fueled your car with corn? You have, if you bought gas within the city of Portland, Oregon. Portland was the first city to require that all gasoline sold within the city limits

Figure 5.22: bacteria use the same type of anaerobic respiration as our muscle cells. Lactic acid reduces competition from other bacteria, and flavors yogurt, as well!

contain at least 10% ethanol. By mid-2006, nearly 6 million "flex-fuel" vehicles – which can use gasoline blends up to 85% ethanol (E85 – **Figure** 5.23) were traveling US roads. This "new" industry employs an "old" crew of yeast and bacteria to make ethanol by an even older biochemical pathway – **alcoholic fermentation**. Many people consider "renewable" biofuels such as ethanol a partial solution to the declining availability of "nonrenewable" fossil fuels. Although controversy still surrounds the true efficiency of producing fuel from corn, ethanol is creeping into the world fuel resource picture (**Figure** 5.24).

Figure 5.23: Ethanol provides up to 85% of the energy needs of new "fuel-flex" cars. Although its energy efficiency is still controversial, ethanol from corn or cellulose appears to be more "renewable" than fossil fuels.

You are probably most familiar with the term "fermentation" in terms of alcoholic beverages. You may not have considered that the process is actually a chemical reaction certain bacteria and yeasts use to make ATP. Like lactic acid fermentation, alcoholic fermentation processes pyruvate one step further in order to regenerate NAD+ so that glycolysis can continue to make ATP. In this form of anaerobic respiration, pyruvate is broken down into ethyl alcohol and carbon dioxide:

$$\mathbf{C_3H_3O_3\ (pyruvate) + NADH \rightarrow C_2H_5OH\ (ethyl\ alcohol) + CO_2 + NAD^+}$$

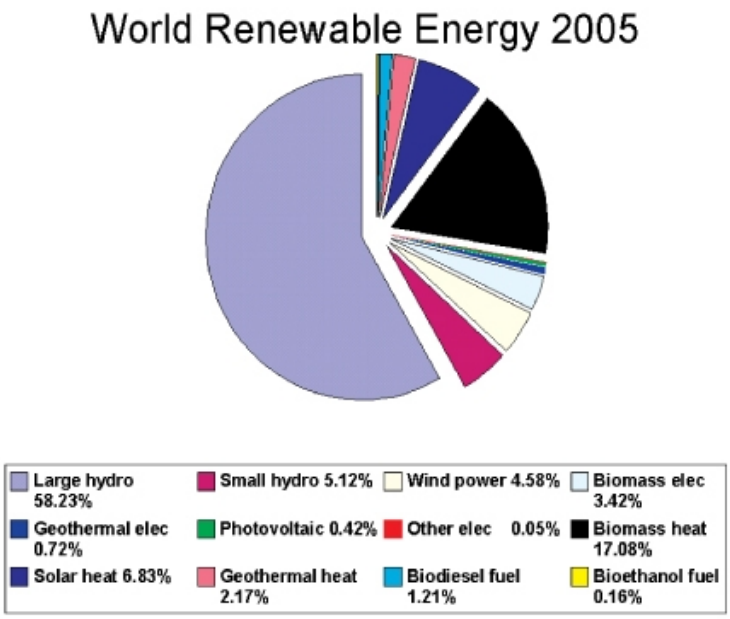


Figure 5.24: One of the newest kids on the block, ethanol from corn or cellulose is produced by yeasts through alcoholic fermentation – an anaerobic type of respiration.

We have domesticated yeast (**Figures** 5.25 and **Figure** 5.26) to carry out this type of anaerobic respiration for many commercial purposes. When you make bread, you employ the yeast to make the bread "rise" by producing bubbles of carbon dioxide gas. Why do you suppose that eating bread does not intoxicate you?

Brewers of beer and wine use yeast to add alcohol to beverages. Traditional varieties of yeast not only make but also limit the quantity of alcohol in these beverages, because above 18% by volume, alcohol becomes toxic to the yeast itself! We have recently developed new strains of yeast which can tolerate up to 25% alcohol by volume. These are used primarily in the production of ethanol fuel.

Human use of alcoholic fermentation depends on the chemical energy remaining in pyruvate after glycolysis. Transforming pyruvate does not add ATP to that produced in glycolysis, and for anaerobic organisms, this is the end of the ATP-producing line. All types of anaerobic respiration yield only 2 ATP per glucose. In the next section, we will compare the advantages and disadvantages of aerobic and anaerobic respiration.

Aerobic vs. Anaerobic Respiration: A Comparison

As aerobes in a world of **aerobic** organisms, we tend to consider aerobic respiration "better" than **fermentation**. In some ways, it is. However, anaerobic respiration has persisted far longer on this planet, through major changes in atmosphere and life. There must be value

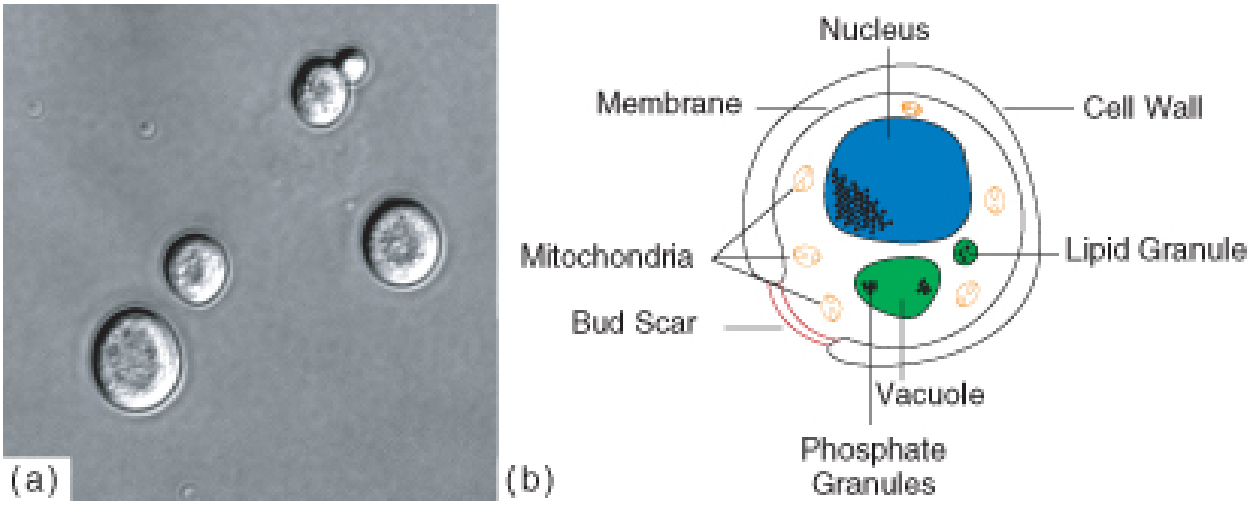


Figure 5.25: Yeasts are facultative anaerobes, which means that in the absence of oxygen, they use alcoholic fermentation to produce ethyl alcohol and carbon dioxide. Both products are important commercially.

Figure 5.26: We employ yeasts to use their anaerobic talents to help bread rise (via bubbles of CO2) and grapes ferment (adding ethanol).

in this alternative way of making ATP. In this last section, we will compare the advantages and disadvantages of these two types of respiration.

A major argument in favor of aerobic over anaerobic respiration is overall energy production. Without oxygen, organisms can only break 6-carbon glucose into two 3-carbon molecules. As we saw earlier, glycolysis releases only enough energy to produce two (net) ATP per molecule of glucose. In contrast, aerobic respiration breaks glucose all the way down to CO_2, producing up to 38 ATP. Membrane transport costs can reduce this theoretical yield, but aerobic respiration consistently produces at least 15 times as much ATP as anaerobic respiration. This vast increase in energy production probably explains why aerobic organisms have come to dominate life on earth. It may also explain how organisms were able to increase in size, adding multicellularity and great diversity.

However, anaerobic pathways persist, and a few obligate anaerobes have survived over 2 billion years beyond the evolution of aerobic respiration. What are the advantages of fermentation?

One advantage is available to organisms occupying the few anoxic (lacking oxygen) niches remaining on earth. Oxygen remains the highly reactive, toxic gas which caused the "Oxygen Catastrophe." Aerobic organisms have merely learned a few tricks – enzymes and antioxidants - to protect themselves. Organisms living in anoxic niches do not run the risk of oxygen exposure, so they do not need to spend energy to build these elaborate chemicals.

Individual cells which experience anoxic conditions face greater challenges. We mentioned earlier that muscle cells "still remember" anaerobic respiration, using lactic acid fermentation to make ATP in low-oxygen conditions. Brain cells do not "remember", and consequently cannot make any ATP without oxygen. This explains why death follows for most humans who endure more than four minutes without oxygen.

Variation in muscle cells gives further insight into some benefits of anaerobic respiration. In vertebrate muscles, lactic acid fermentation allows muscles to produce ATP quickly during short bursts of strenuous activity. Muscle cells specialized for this type of activity show differences in structure as well as chemistry. Red muscle fibers are "dark" because they have a rich blood supply for a steady supply of oxygen, and a protein, myoglobin, which holds extra oxygen. They also contain more mitochondria, the organelle in which the Krebs cycle and electron transport chain conclude aerobic respiration. White muscle cells are "light" because they lack the rich blood supply, have fewer mitochondria, and store glycogen rather than oxygen. When you eat dark meat, you are eating endurance muscle. When you eat white meat, you are eating muscle built for sprinting.

Each type of muscle fiber has advantages and disadvantages, which reflect their differing biochemical pathways. Aerobic respiration in red muscles produces a great deal of ATP from far less glucose - but slowly, over a long time. Anaerobic respiration in white muscles produces ATP rapidly for quick bursts of speed, but a predator who continues pursuit may eventually catch a white-muscled prey.

In summary, aerobic and anaerobic respiration each have advantages under specific conditions. Aerobic respiration produces far more ATP, but risks exposure to oxygen toxicity. Anaerobic respiration is less energy-efficient, but allows survival in habitats which lack oxygen. Within the human body, both are important to muscle function. Muscle cells specialized for aerobic respiration provide endurance, and those specialized for lactic acid fermentation support short but intense energy expenditures. Both ways of making ATP play critical roles in life on earth.

Lesson Summary

- In the two to three billion years since photosynthesis added oxygen to earth's atmosphere, life has become mostly aerobic. Some organisms and types of cells retain the older, anaerobic pathways for making ATP; these pathways comprise anaerobic respiration or fermentation.
- Obligate aerobes require oxygen to make ATP. Obligate anaerobes cannot survive in the presence of oxygen, so they occupy only anoxic habitats. Facultative anaerobes make ATP with oxygen, but if oxygen levels become low, they can use fermentation.
- Some bacteria, including those we employ to make yogurt, make ATP using lactic acid fermentation; the acid may help reduce competition from other bacteria. Muscle cells can continue to produce ATP when O_2 runs low using lactic acid fermentation, but muscle fatigue and pain may result.
- Red muscle fibers use mostly aerobic respiration to make ATP for endurance tasks; white muscle fibers use mostly lactic acid fermentation to make ATP quickly for short, intense activities. Human muscles contain a mixture of red and white fibers, but genetics may give sprinters more white fibers, and marathoners more red.
- Both alcoholic and lactic acid fermentation pathways change pyruvate in order to continue producing ATP by glycolysis.
- Ethanol produced by bacteria through alcoholic fermentation of corn (and perhaps other fuels in the near future) may provide a more renewable fuel for vehicles than the fossil fuels upon which we currently depend. We employ yeasts to help make bread through alcoholic fermentation; as they produce carbon dioxide, the bread dough rises. We employ anaerobic organisms to make beer and wine through alcoholic fermentation; the alcohol content is limited to 18% by volume because levels above that are toxic to these organisms.
- Aerobic respiration is far more energy-efficient than anaerobic respiration. Aerobic processes produce up to 38 ATP per glucose. Anaerobic processes yield only 2 ATP per glucose.

Review Questions

1. Classify your own cells as obligate aerobes, obligate anaerobes, or facultative anaerobes, and explain your reasoning. (Although these terms usually apply to whole organisms, assume they can also apply to individual cells within your body).
2. Identify yourself as a "sprinter" or an "endurance runner" and predict the type of muscle fiber (red or white) which predominates in your body. Explain your reasoning.
3. Construct a chart which compares alcoholic to lactic acid fermentation, considering at least three different features.
4. Outline the process used to produce fuel from corn and explain why some consider this fuel "renewable" and preferable to fossil fuels. Research the pros and cons of this fuel.
5. Explain how fermentation is used to make bread.
6. If two species of bacteria – one using aerobic respiration and the other using anaerobic respiration - were competing for the same source of glucose in the same environment, which one would out-compete the other? Explain why.
7. Human cells cannot carry out alcoholic fermentation, yet we use it for many purposes. Analyze its importance to human life.
8. Explain why both types of fermentation must change pyruvic acid, even though no energy is gained in this conversion.
9. Indicate the maximum alcohol content of wine and beer, and explain the reason for this limit.
10. Construct a chart comparing aerobic to anaerobic respiration using at least 5 characteristics.

Further Reading / Supplemental Links

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Vocabulary

aerobic With oxygen, or living or occurring only in the presence of oxygen.

alcoholic fermentation The process for making ATP in the absence of oxygen, by converting glucose to ethanol and carbon dioxide.

anaerobic Without oxygen; living or occurring in the absence of oxygen.

facultative anaerobe An organism which can respire aerobically when oxygen is present, but is also capable of fermentation when oxygen levels are low.

glycolysis The process of "splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

lactic acid fermentation The process for making ATP in the absence of oxygen by converting glucose to lactic acid.

obligate aerobe An organism which requires oxygen for cellular respiration.

obligate anaerobe An organism which uses anaerobic respiration, and dies in the presence of oxygen.

Points to Consider

- Humans seem to harness anaerobic respiration much more than aerobic respiration to create useful products, such as foods or fuels. Use your understanding of the two processes to explain why this makes sense.
- Some controversy exists over whether or not ethanol produced by fermentation of corn is an efficient and wise way to produce fuel. Can you think of some reasons, pro and/or con?
- How might the wing muscles of birds which migrate long distances compare to those of birds which do not migrate? Why do you suppose human muscles are mixtures of red and white fibers, rather than specialized, as in many birds?

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Chapter 6

Cell Division and Reproduction

6.1 Lesson 6.1: Chromosomes and the Cell Cycle

Lesson Objectives

- Describe the properties of cell division in prokaryotes.
- Describe cell division in eukaryotes. Explain the main differences between cell division in prokaryotic and eukaryotic cells.
- Describe the basic properties of chromosomes.
- Describe the key steps in the cell cycle.
- Identify and describe the main processes in mitosis.
- Describe how the cell cycle is controlled and define cancer.

Introduction

You are made of many different types of cells. Nerve cells, skin cells, muscle cells, and many more. These cells obviously have many different functions, yet they all develop from the first cell that makes you. So do they all have the same DNA? Are all the cells in your body genetically identical? How does the first cell of an organism know to become two cells, then four cells, and so on? What tells these cells what to do? Your body produces about 25 million genetically identical cells every second. These new cells are formed when older cells divide, a process called cell division or cell reproduction.

Cell division is the final step in the life of a cell, otherwise known as the cell cycle. Eukaryotic cells and prokaryotic cells complete this process by a number of different mechanisms. The cell cycle is a repeating series of events, during which the eukaryotic cell carries out its necessary functions, including metabolism, cellular growth, and division, resulting in two genetically identical daughter cells. To produce two genetically identical daughter cells, the

chromosomes need to replicate and the nucleus and cytoplasm need to divide. These are key events in the life of a cell.

Cell Division in Prokaryotes

Prokaryotic organisms reproduce asexually by **binary fission**, a process that produces identical offspring (**Figure** 6.1). In asexual reproduction, a single parent produces genetically identical offspring. As prokaryotes do not have a nucleus, and have only one circular chromosome, they do not need to reproduce by the same mechanism as eukaryotic cells. Prokaryotic cell division is a much simpler process. In prokaryotic cell division, after the single chromosome is copied, the cell grows larger. Eventually the two chromosomes separate and move to opposite ends of the cell. Newly formed cell membrane then grows into the center of the cell, separating the two chromosomes, and forming two genetically identical daughter cells. The formation of two daughter cells is called cytokinesis.

Under ideal conditions, reproduction in bacteria is extremely efficient, with some bacteria reproducing every 20 minutes. This makes bacteria an extremely effective tool for the molecular biologist. However, bacteria do not usually live in ideal conditions; otherwise, bacteria would grow and divide extremely rapidly, eventually covering the surface of Earth. Bacterial growth is limited by nutrients and water, predation, and by their own wastes.

Cell Division in Eukaryotes

Cell division in eukaryotic organisms is very different from that in prokaryotes, mainly because of the many chromosomes in the nuclei of eukaryotic cells. Cell division in eukaryotic organisms is necessary for development, growth, and repair. This cell division ensures that each resulting daughter cell receives a complete copy of the organism's entire genome. Remember that all of an organism's DNA must be present in each somatic, or body, cell. This DNA contains the information necessary for that cell to perform its functions, and to give that organism its traits. Therefore, prior to cell division, the eukaryotic cell's complete genome must be copied, ensuring that each daughter cell receives a complete set of the genome.

The formation of **gametes**, an organism's reproductive cells, such as sperm and egg cells, involves a completely different method of cell division. This cell division ensures that each gamete receives half the amount of an organism's DNA.

DNA, Chromosomes, and Genes

As previously discussed (in the *Foundations of Life Science* chapter), DNA contains the information necessary to make proteins, direct a cell's activities, and give an organism its traits. This information is organized into structural units scattered along the length of the

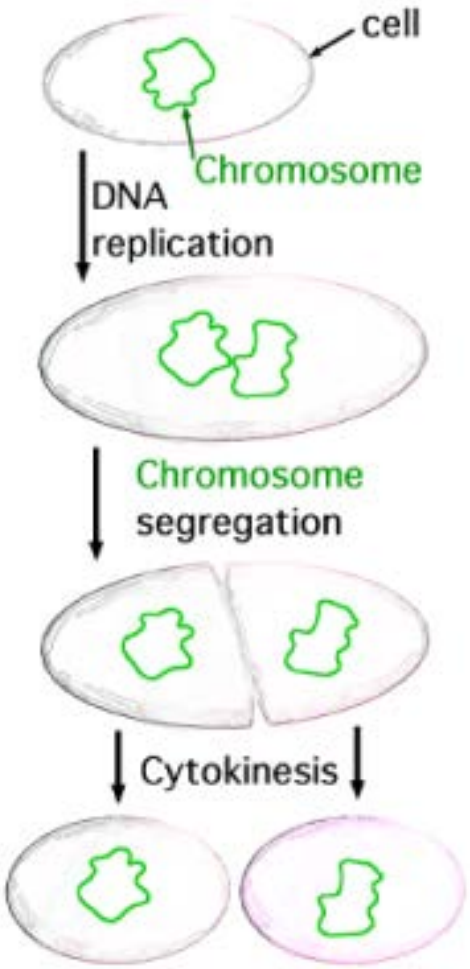

Figure 6.1: Binary fission. In binary fission, the single chromosome is copied and eventually separates into two separate chromosomes, the cell grows larger, and two identical cells form by cytokinesis.

DNA molecule. These units are known as **genes**. A gene contains the information necessary to encode an RNA molecule or a protein. A single DNA molecule contains hundreds to thousands of genes. Different cell types use the information in different genes to make different proteins. This process gives different cell types distinct activities. Thus, a liver cell will have many different proteins than a kidney cell, giving the two cells types distinct activities. When a cell is using the information within a gene, the segment of DNA containing that gene is unwound, exposing the double helix to the cell machinery needed to use that information.

Prior to cell division, the DNA must duplicate itself in a process called DNA replication. This ensures that each resulting cell receives a complete set of the organism's genome. But how is the replicated DNA divided up evenly? What guarantees that each new cell will receive a complete set of DNA? It was the identification of chromosomes that allowed this process to be characterized. As a eukaryotic cell prepares to divide, the DNA and associated proteins (histones) coil into a structure, known as a **chromosome** (**Figure** 6.2). The DNA copies itself prior to this process, so the chromosome that forms consists of two identical chromatids, known as **sister chromatids**, identical copies of DNA. The two chromatids are attached at a region called the **centromere.** The chromatids separate from each other when the nucleus divides just prior to cell division. Thus, each new cell that results after cell division will have the complete amount of genetic material, identical to the original, or parent, cell. In human cells, this amounts to 46 chromosomes. These chromosomes come in pairs (one from each pair inherited from each parent). So these 46 chromosomes are actually two sets of 23 chromosomes each. For an animation of how the DNA coils into a chromosome, see http://www.hhmi.org/biointeractive/media/DNAi_packaging_vo2-sm.mov.

Each human somatic cell (a body cell, or every cell other than a gamete) normally has two sets of chromosomes, one set inherited from each parent. Each set contains 23 chromosomes, for a total of 46 chromosomes. Each chromosome differs in size, from over 250 million nucleotide pairs to less than 50 million nucleotide pairs. Each chromosome contains a specific set of genes, making each chromosome essential to survival.

Each pair of chromosomes consists of two chromosomes that are similar in size, shape, and genes. These pairs of chromosomes are known as **homologous chromosomes**, or **homologues**. Upon fertilization, a **zygote** is formed (**Figure** 6.3). A zygote is the first cell of a new individual. In humans, a zygote contains 23 pairs (or two sets) of chromosomes. Any cell containing two sets of chromosomes is said to be **diploid**. The zygote forms from the fusion of two **haploid** gametes. A haploid cell contains one set of chromosomes. In humans, a haploid gamete contains 23 chromosomes. Biologists use the symbol n to represent one set of chromosomes, and $2n$ to represent two sets. In humans, each set of chromosomes contains 22 **autosomes** and 1 sex chromosome. Autosomes are chromosomes that are not directly involved in determining the sex of an individual. The sex chromosomes contain genes that determine the sex of an individual.

Whereas autosomes are found as homologous pairs in somatic cells, sex chromosomes come in two different sizes, shapes, and contain different genes. In many organisms, including

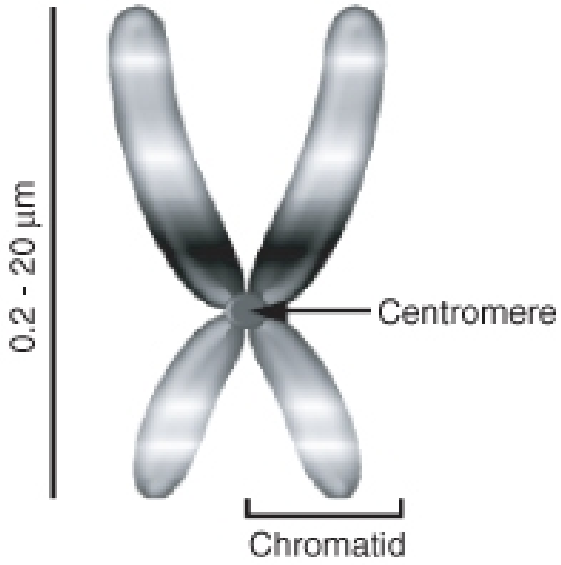

Figure 6.2: A representation of a condensed eukaryotic chromosome, as seen after the DNA has been copied. The chromosome is made of two identical, or sister, chromatids held together by a centromere.

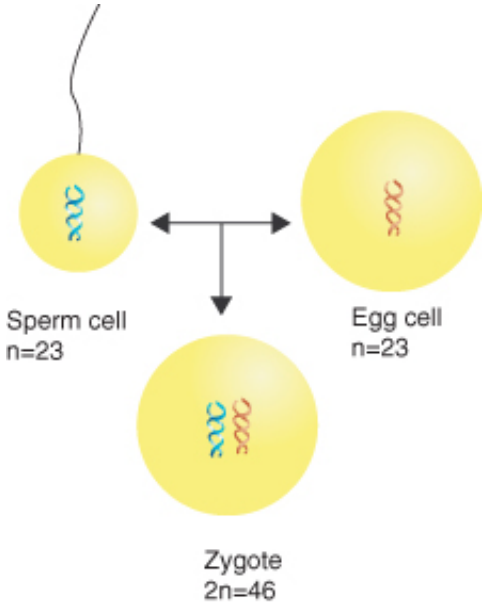

Figure 6.3: Upon fertilization a diploid zygote is formed. In humans, a zygote has 46 chromosomes, 23 inherited from each parent. The gametes, sperm and eggs, are haploid cells, with 23 chromosomes each.

humans, the sex chromosomes are known as the X and Y chromosomes. The Y chromosome contains genes that cause male development. Therefore, any individual with a Y chromosome is male, and a male will have both an X and Y chromosome (XY). Females, without a Y chromosome, will have two X chromosomes (XX). As females have two X chromosomes, they must pass an X chromosome to all of their children. As males have both an X chromosome (inherited from their mother) and a Y chromosome, they can give either chromosome to their children. If a child inherits a Y from his father, he will be male; if a child inherits an X from her father, she will be female. It therefore is the male gamete that determines the sex of the offspring.

The Cell Cycle

Cell division in eukaryotic cells is much more complex than in prokaryotic cells because of the many chromosomes within the nucleus. Both the cytoplasm and the genetic material must be divided, ensuring that each resulting daughter cell receives 46 separate chromosomes. To ensure this, in addition to the cell performing its necessary functions, the DNA must be copied, as must many organelles, prior to cell division.

The life of a eukaryotic cell is a cycle, known as the **cell cycle** (**Figure** 6.4). The cell cycle is a repeating series of cellular growth and division. The cell cycle has five phases: the first growth (G_1) phase, the synthesis (S) phase, the second growth (G_2) phase, mitosis, and

cytokinesis, though many consider mitosis and cytokinesis to be combined into one phase. The cell spends the majority of the cycle in the first three phases of the cycle, collectively known as **interphase**. After cytokinesis, two genetically identical daughter cells are formed.

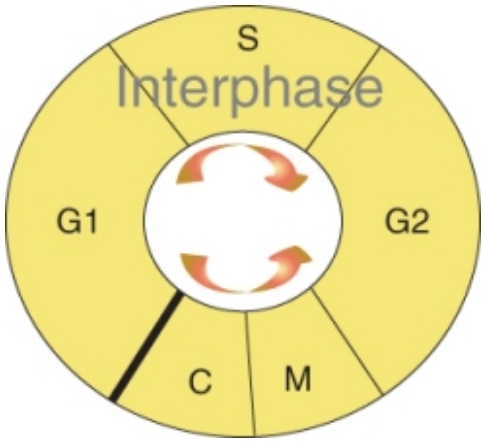

Figure 6.4: The Cell Cycle. The cell cycle depicts the life of an eukaryotic cell. The cell cycle has five phases: the first growth (G) phase, the synthesis (S) phase, the second growth (G) phase, mitosis (M), and cytokinesis (C). The cell spends the majority of the cycle in the first three phases (G, S, G) of the cycle, collectively known as interphase. After cytokinesis, two genetically identical daughter cells are formed. Many consider the cell cycle to only have four phases, with mitosis and cytokinesis combined. has an excellent animation of the cell cycle.

The first growth (G_1) phase: The cell spends most of its life in the G_1 phase. During this phase, a cell undergoes rapid growth and the cell performs its routine functions. If a cell is not dividing, the cell remains in this phase.

The synthesis (S) phase: For two genetically identical daughter cells to be formed, the cell's DNA must be copied or replicated. When the DNA is replicated, both strands of the double helix are used as templates to produce two new complementary strands. These new strands then hydrogen bond to the template strands and two double helices form.

The second growth (G_2) phase is a shortened growth period in which many organelles are reproduced or manufactured. Parts necessary for cell division are made during G_2.

Mitosis is the phase of nuclear division, in which one nucleus divides and becomes two nuclei. After mitosis is **cytokinesis**, in which the cytoplasm divides in half, producing two daughter cells, each containing a complete set of genetic material.

Mitosis

Mitosis is the division of the cell's nucleus, the final step before two daughter cells are produced. The cell enters mitosis as it approaches its size limitations. Four distinct phases

of mitosis have been recognized: *prophase, metaphase, anaphase, and telophase,* with each phase merging into the next one (**Figure** 6.5).

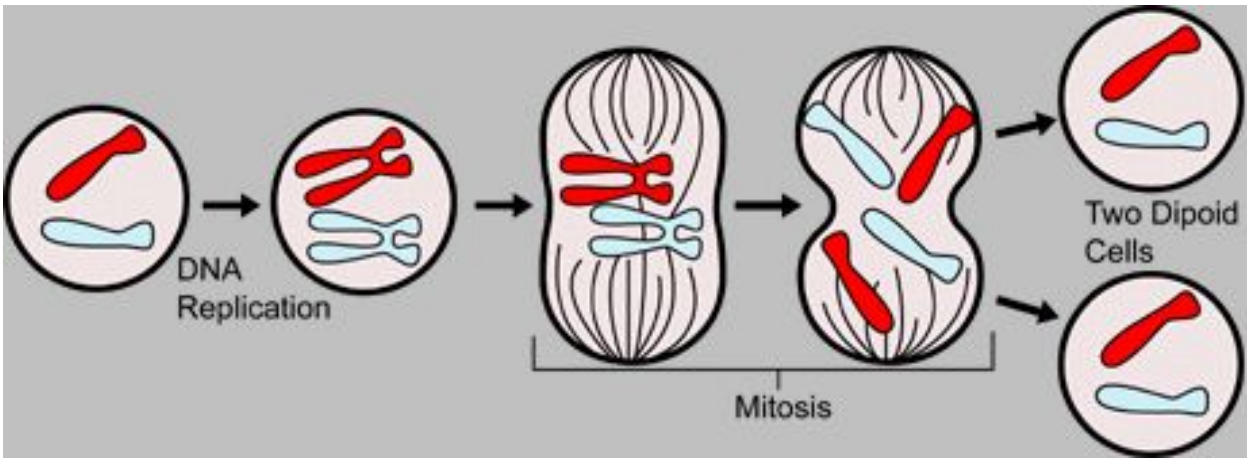

Figure 6.5: During mitosis, the nucleus divides, paving the way for two cells to be produced after cell division, each with a complete makeup of genetic material. has an excellent animation of mitosis.

Prophase is the first and longest phase of mitosis. During prophase, the DNA coils up into visible chromosomes, each made up of two sister chromatids held together by the centromere. The nucleus disappears as the nuclear envelope and nucleolus break apart. The centrioles begin to move to opposite ends, or poles, of the cell. As the centrioles migrate, the fiber-like spindle begins to elongate between the centrioles. The spindle is a thin, cage-like structure made out of microtubules. In plant cells, the spindle forms without centrioles. The spindle plays an essential role moving chromosomes and in the separation of sister chromatids.

During metaphase the spindle attaches to the centromere of each chromosome. Helped by the spindle, the chromosomes line up at the center, or equator, of the cell, also known as the metaphase plate. Each sister chromatid is attached to a separate spindle fiber, with one fiber extending to one pole, and the other fiber extending to the other pole. This ensures that the sister chromatids separate and end up in distinct cells after cell division.

Anaphase is the phase in which the sister chromatids separate. The sister chromatids are pulled apart by the shortening of the microtubules of the spindles, similar to the reeling in of a fish by the shortening of the fishing line. One sister chromatid moves to one pole of the cell, and the other sister chromatid moves to the opposite pole. At the end of anaphase, each pole of the cell has a complete set of chromosomes, identical to the amount of DNA at the beginning of G_1 of the cell cycle.

Telophase is essentially the opposite of prophase. The chromosomes begin to unwind in preparation to direct the cell's metabolic activities. The spindle begins to break down, allowing a new nucleus to form. This is followed by cytokinesis, the division of the cytoplasm,

resulting in two genetically identical cells, ready to enter G_1 of the next cell cycle. The phases of mitosis are summarized in **Figure** 6.6.

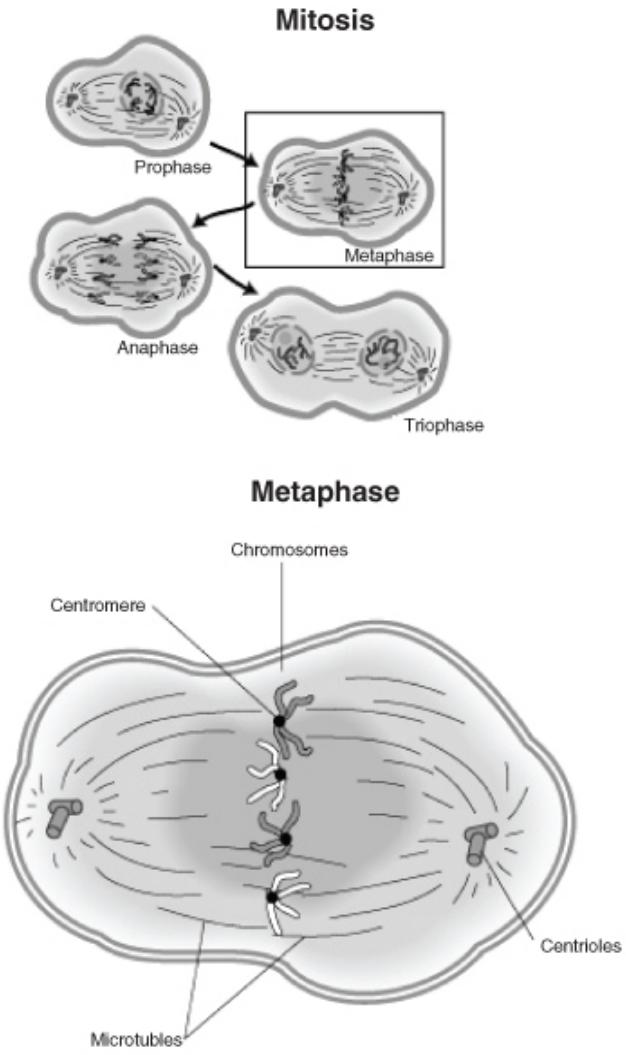

Figure 6.6: Mitosis. The phases of mitosis are depicted. The second phase, metaphase, is shown with the chromosomes lined up at the equator of the cell and the microtubule spindle fibers extending from the centrioles to the centromeres of the chromosomes.

Cytokinesis (**Figure** 6.7) differs between plant and animal cells. In animal cells, the plasma membrane pinches inward along the cell's equator until two cells are formed. In plant cells, a cell plate forms along the cells equator. A new membrane grows along each side of the cell plate, with a new cell wall forming on the outside of each new membrane.

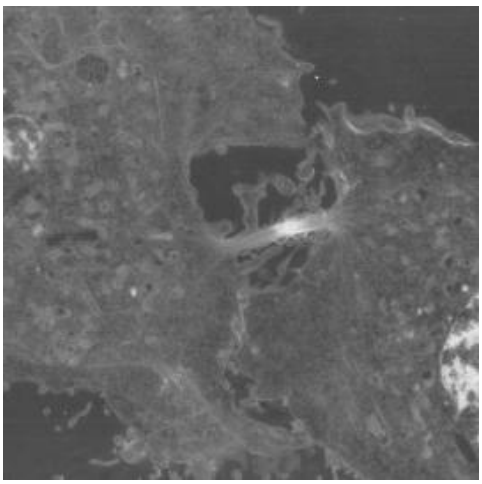

Figure 6.7: Cytokinesis. In this electron micrograph of a cell, two formation of two new cells is almost complete, as new membrane grows and divides the parent cell.

Control of the Cell Cycle

How does the cell know when to divide? How does the cell know when to replicate the DNA? The answers to these questions have to do with the control of the cell cycle. But how is the cell cycle controlled?

The cell cycle is controlled by a number of protein-controlled feedback processes. Two types of proteins involved in the control of the cell cycle are kinases and cyclins. Cyclins activate kinases. Cyclins are a group of proteins that is rapidly produced at key stages in the cell cycle. Kinases activate other target molecules. It is this precise regulation of proteins that triggers advancement through the cell cycle.

The cell cycle has key checkpoints. When the cell receives key signals or information (feedback regulation), the cell can begin the next phase of the cell cycle. The cell can also receive signals that delay passage to the next phase of the cell cycle. These signals allow the cell to complete the previous phase before moving forward. Three key checkpoints are the cell growth (G_1) checkpoint, the DNA synthesis (G_2) checkpoint, and the mitosis checkpoint.

The cell growth (G_1) checkpoint allows the cell to proceed into the S phase of the cell cycle and continue on to divide. The cell spends most of the cycle in the G_1 phase. G_1 is where the cell carries out its main functions. If the cell has performed its functions and has grown to significant size to be divided in half, key proteins will stimulate DNA replication to begin. If the cells are not to divide, such as some muscle and nerve cells, the cell will stop at this checkpoint and move into a resting phase. Some cells may stay in this resting period permanently, never dividing.

The DNA synthesis (G_2) checkpoint determines if the cell is ready for mitosis. DNA repair enzymes check the replicated DNA at this point. If the checkpoint is passed, the many

molecular mechanisms and processes needed for mitosis will begin.

The mitosis checkpoint determines the end of one cycle and the beginning of the next. This checkpoint signals the end of mitosis, allowing the cell to prepare for the beginning of G_1 of the next cell cycle.

Cancer and the Cell Cycle

Many cancers result from uncontrolled cell division, when the regulation of the cycle is lost (**Figure** 6.8). Cancerous cells divide much more rapidly than healthy cells. These cells use the blood and nutrients that other cells need and they can stress the environment of the healthy cells. As cancerous cells do not provide any useful function to the organism, they are extremely harmful. If cancerous cells are allowed to grow uncontrolled, they will kill the host organism. Many cancerous cells are the products of normal cells that have lost the ability to regulate the cell cycle. The genes that encode the proteins involved in cell cycle regulation have mutations. One category of genes, called oncogenes, accelerate the cell cycle. Many cancers can be inherited, such as breast cancer. Others are triggered by an environmental stimulus, such as through the relationship between tobacco smoke and lung cancer, or ultraviolet radiation and skin cancer.

Lesson Summary

- The cell cycle is a repeating series of events, characterizing the life of a eukaryotic cell.
- Binary fission is a form of cell division in prokaryotic organisms that produces identical offspring.
- As a eukaryotic cell prepares to divide, the DNA and associated proteins coil into a structure, known as a chromosome.
- The DNA copies during the S phase of the cell cycle, resulting in a chromosome that consists of two identical chromatids, known as sister chromatids, attached at a region called the centromere.
- Any cell containing two sets of chromosomes is said to be diploid; the zygote forms from the fusion of two haploid gametes.
- The cell cycle has five phases: the first growth (G_1) phase, the synthesis (S) phase, the second growth (G_2) phase, mitosis, and cytokinesis.
- Mitosis is the division of the nucleus; four distinct phases of mitosis have been recognized: prophase, metaphase, anaphase, and telophase.
- Cytokinesis is the division of the cytoplasm.
- The cell cycle is controlled through feedback mechanisms.
- Cancer results from uncontrolled cell division, due to the loss of regulation of the cell cycle.

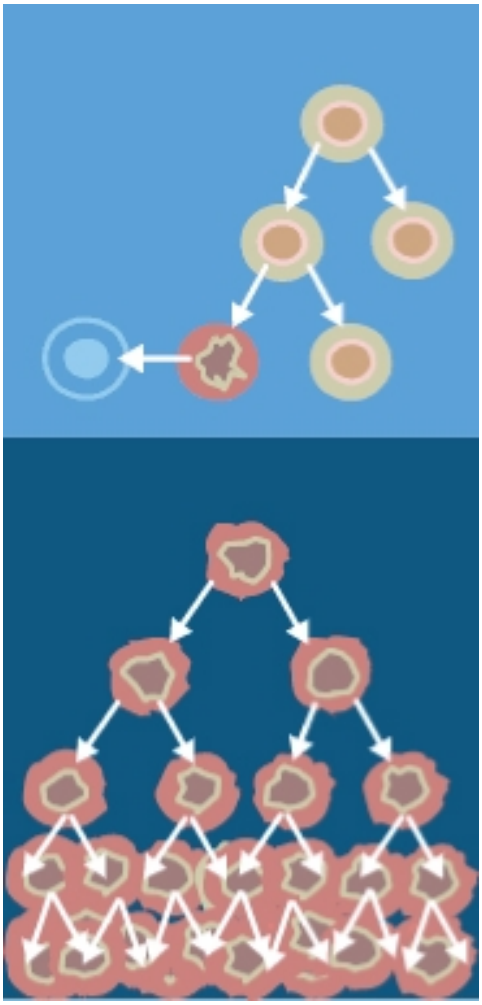

Figure 6.8: When normal cells are damaged beyond repair, they are eliminated. (A) diagrams damaged cells being destroyed. Cancer cells avoid elimination and, because of uncontrolled cell division, continue to multiply in an unregulated manner. (B) depicts damaged cells dividing in an uncontrolled fashion.

Review Questions

1. How does cell division in bacteria differ from mitosis in eukaryotes?
2. Describe the structure of a chromosome in prophase of mitosis.
3. What is cytokinesis and when does it occur?
4. What is a centromere?
5. Describe interphase.
6. Describe the main steps of mitosis.
7. What is binary fission?
8. Define a gene.

Further Reading / Supplemental Links

- http://www.genome.gov
- http://www.cellsalive.com/mitosis.htm
- http://www.cellsalive.com/cell_cycle.htm
- http://biology.clc.uc.edu/courses/bio104/mitosis.htm
- http://nobelprize.org/educational_games/medicine/2001

Vocabulary

autosomes Chromosomes that are not directly involved in determining the sex of an individual.

binary fission Asexual reproduction in prokaryotic organisms; produces identical offspring.

cancer Disease that can result from uncontrolled cell division, when the regulation of the cycle is lost.

cell cycle A repeating series of events, during which the eukaryotic cell carries out its necessary functions, including metabolism, cellular growth, and division, resulting in two genetically identical daughter cells.

cell division Process of cell formation from the division of older cells.

cell plate Forms during cytokinesis in plant cells; a new membrane grows along each side of the cell plate, with a new cell wall forming on the outside of each new membrane.

centriole Structure from which spindle fibers originate.

centromere Region that attaches two sister chromatids; approximately near the middle of a chromosome.

chromosome Coiled structure of DNA and histone proteins; allows for the precise separation of replicated DNA; forms during prophase of mitosis and meiosis.

cyclins A group of proteins that is rapidly produced at key stages in the cell cycle; activate kinases; participate in the regulation of the cell cycle.

cytokinesis Division of the cytoplasm, forming two daughter cells.

diploid A cell containing two sets of chromosomes; in human cells, two sets contains 46 chromosomes.

DNA replication Process by which the DNA is copied, resulting in two identical copies.

gametes An organism's reproductive cells, such as sperm and egg cells.

gene A segment of DNA that contains the information necessary to encode an RNA molecule or a protein.

haploid A cell containing one set of chromosomes; in human gametes, one set is 23 chromosomes.

homologous chromosomes A pair of chromosomes (one from each parent) consisting of two chromosomes that are similar in size, shape, and genes; also known as homologues.

interphase The first three phases of the cell cycle; the cell spends the majority of its time here.

kinases Proteins involved in the regulation of the cell cycle; activated by cyclins; activate other target molecules.

metaphase plate The center (equator) of a cell during mitosis; chromosomes line up at the metaphase plate to ensure the proper separation of the chromatids.

mitosis The division of the nucleus into two genetically identical nuclei.

oncogene Cancer causing gene; can accelerate the cell cycle.

resting phase Phase associated with the G_1 phase of the cell cycle; cells that do not divide are in a resting phase and do not continue to the S phase.

S phase Synthesis phase; the phase of the cell cycle in which the DNA is replicated (copied).

sex chromosomes Contain genes that determine the sex of an individual.

sister chromatid Identical copies of a DNA molecule; a chromosome at the start of mitosis and meiosis has two sister chromatids.

spindle Thin, cage-like fibers made out of microtubules; used to move chromosomes and to separate the sister chromatids during mitosis.

zygote The first cell of a new individual.

Points to Consider

- A human cell has 46 chromosomes, while a bacterial cell has only one chromosome. Would you think that the number of chromosomes relates to the complexity of the cell or organism?
- Mitosis and cytokinesis produce two genetically identical daughter cells. Think about how a cell with half as much DNA, such as a sex cell, may form.
- As not every species has members of the opposite sex, such as bacteria, yet all organisms must reproduce to stay alive, think about how these sexless organisms may reproduce.

6.2 Lesson 6.2: Meiosis

Lesson Objectives

- Describe asexual reproduction; explain the genetic relationship between parent and offspring.
- Describe sexual reproduction; explain the genetic relationship between parent and offspring.
- Identify and describe the main steps of meiosis, distinguishing between the quantity of genetic material in the parent and resulting cells.
- Describe gametogenesis and identify the key differences between oogenesis and spermatogenesis.
- Distinguish between the three types of sexual life cycles.

Introduction

Some organisms look and act exactly like their parent. Others share many similar traits, but they are definitely unique individuals. Some species have two parents, whereas others have just one. How an organism reproduces determines the amount of similarity the organism will have to its parent. Asexual reproduction produces an identical individual, whereas sexual reproduction produces a similar, but unique, individual. In sexual reproduction, meiosis produces haploid gametes that fuse during fertilization to produce a diploid zygote (**Figure** 6.9 and **Figure** 6.11).

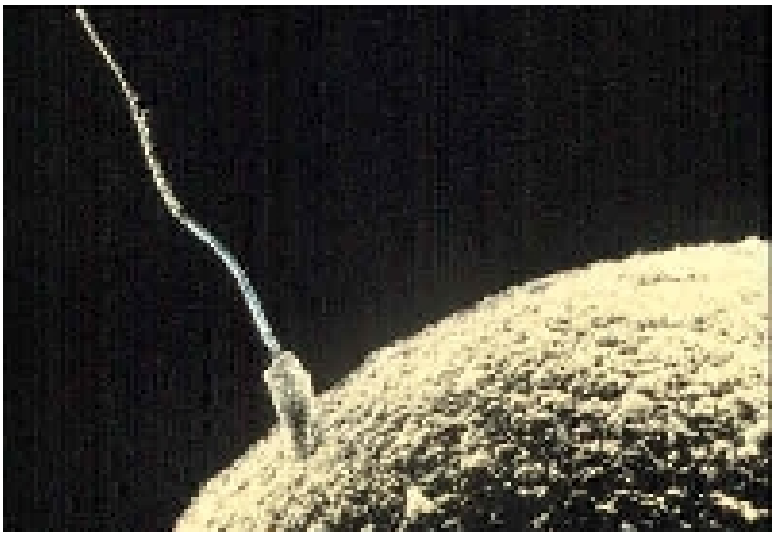

Figure 6.9: Fertilization of an egg cell by a sperm cell. In sexual reproduction, haploid gametes fuse to produce a diploid zygote.

Asexual Reproduction

Are there male and female bacteria? How could you tell? Remember, bacteria have just one chromosome; they do not have an X or Y chromosome. So they probably have a very simplified form of reproduction. Asexual reproduction, the simplest and most primitive method of reproduction, produces a **clone**, an organism that is genetically identical to its parent. Haploid gametes are not involved in asexual reproduction. A parent passes all of its genetic material to the next generation. All prokaryotic and many eukaryotic organisms reproduce asexually.

There are a number of types of asexual reproduction including fission, fragmentation and budding. In fission, a parent separates into two or more individuals of about equal size. In fragmentation, the body breaks into several fragments, which later develop into complete adults. In budding, new individuals split off from existing ones. The bud may stay attached

or break free from the parent. Eukaryotic organisms, such as the single cell yeast and multicellular hydra, undergo budding (**Figure** 6.10).

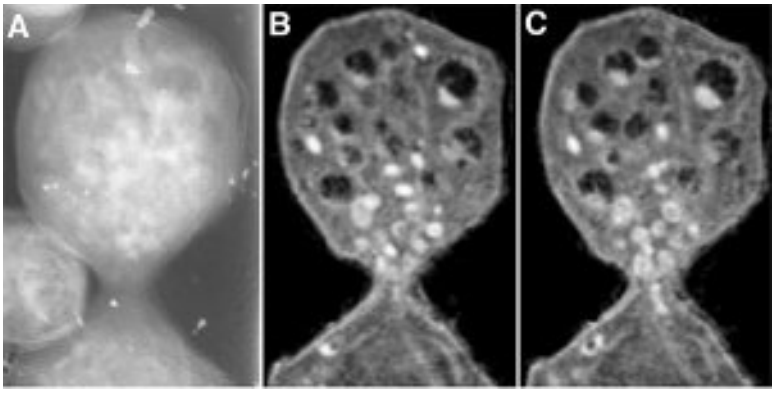

Figure 6.10: Magnification of a budding yeast.

Sexual Reproduction and Meiosis

Why do you look similar to your parents, but not identical? First, it is because you have two parents. Second, it is because of sexual reproduction.

Whereas asexual reproduction produces genetically identical clones, sexual reproduction produces genetically diverse individuals. As both parents contribute half of the new organism's genetic material, the offspring will have traits of both parents, but will not be exactly like either parent.

Organisms that reproduce sexually by joining gametes, a process known as fertilization, must have a mechanism to produce haploid gametes. This mechanism is meiosis, a type of cell division that halves the number of chromosomes. During meiosis the pairs of chromosomes separate and segregate randomly to produce gametes with one chromosome from each pair. Meiosis involves two nuclear and cell divisions without an interphase in between, starting with one diploid cell and generating four haploid cells (**Figure** 6.11). Each division, named meiosis I and meiosis II, has four stages: prophase, metaphase, anaphase, and telophase. These stages are similar to those of mitosis, but there are distinct and important differences.

Prior to meiosis, the cell's DNA is replicated, generating chromosomes with two sister chromatids. A human cell prior to meiosis will have 46 chromosomes, 22 pairs of homologous autosomes, and 1 pair of sex chromosomes. Homologous chromosomes are similar in size, shape, and genetic content. You inherit one chromosome of each pair from your mother and the other one from your father.

The 8 stages of meiosis are summarized below. The stages will be described for a human cell, starting with 46 chromosomes.

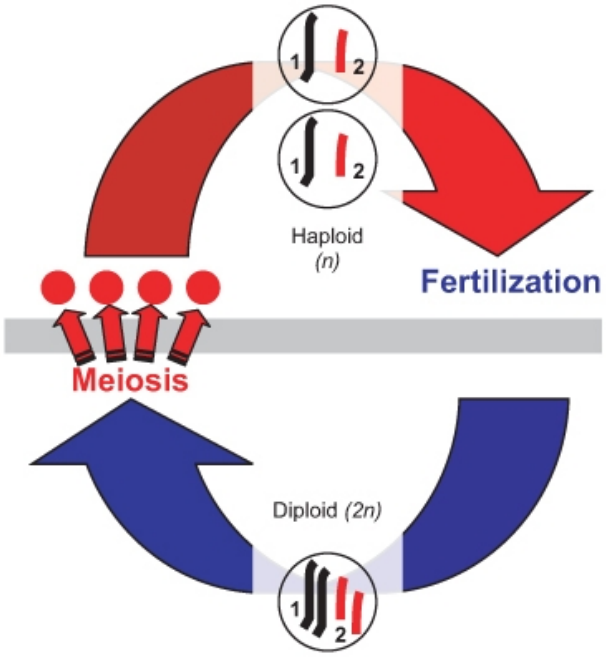

Figure 6.11: During meiosis the number of chromosomes is reduced from a diploid number (2n) to a haploid number (n). During fertilization, haploid gametes come together to form a diploid zygote and the original number of chromosomes (2n) is restored.

Prophase I: prophase I is very similar to prophase of mitosis, but with one very significant difference. In Prophase I, the nuclear envelope breaks down, the chromosomes condense, and the centrioles begin to migrate to opposite poles of the cell, with the spindle fibers growing between them. During this time, the homologous chromosomes form pairs. These homologous chromosomes line up gene-for-gene down their entire length, allowing crossing-over to occur. This is an important step in creating genetic variation and will be discussed later.

Metaphase I: In metaphase I, the 23 pairs of homologous chromosomes line up along the equator of the cell. During mitosis, 46 individual chromosomes line up during metaphase. Some chromosomes inherited from the father are facing one side of the cell, and some are facing the other side.

Anaphase I: During anaphase I the spindle fibers shorten, and the homologous chromosome pairs are separated from each other. One chromosome from each pair moves toward one pole, with the other moving toward the other pole, resulting in a cell with 23 chromosomes at one pole and the other 23 at the other pole. The sister chromatids remain attached at the centromere. Because human cells have 23 pairs of chromosomes, this independent assortment of chromosomes produces 2^{23}, or 8,388,608 possible configurations. More on independent assortment of chromosomes will be presented in the chapter on Mendelian Genetics.

Telophase I: The spindle fiber disassembles and the nucleus reforms. This is quickly followed by cytokinesis and the formation of two haploid cells, each with a unique combination of chromosomes, some from the father and the rest from the mother. After cytokinesis, both cells immediately enter meiosis II; the DNA is not copied in between. Meiosis II is essentially the same as mitosis, separating the sister chromatids from each other.

Prophase II: Once again the nucleus breaks down, and the spindle begins to reform as the centrioles move to opposite sides of the cell.

Metaphase II: The spindle fibers align the 23 chromosomes, each made out of two sister chromatids, along the equator of the cell.

Anaphase II: The sister chromatids are separated and move to opposite poles of the cell. As the chromatids separate, each is known as a chromosome. Anaphase II results in a cell with 23 chromosomes at each end of the cell; each chromosome contains half as much genetic material as at the start of anaphase II.

Telophase II: The nucleus reforms and the spindle fibers break down. Each cell undergoes cytokinesis, producing four haploid cells, each with a unique combination of genes and chromosomes.

- An excellent animation depicting meiosis can be viewed at

http://www.youtube.com/watch?v=D1_-mQS_FZ0&feature=related.

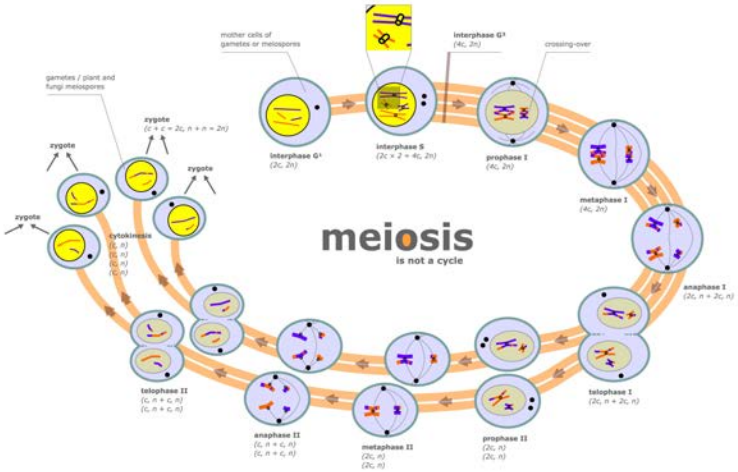

Figure 6.12: Meiosis is a process in which a diploid cell divides itself into four haploid cells. represents the number of chromosomes, represents a haploid cell, represents a diploid cell.

Meiosis and Genetic Variation

Sexual reproduction results in infinite possibilities of genetic variation. This occurs through a number of mechanisms, including crossing-over, the independent assortment of chromosomes during anaphase I, and random fertilization.

Crossing-over occurs during prophase I. Crossing-over is the exchange of genetic material between non-sister chromatids of homologous chromosomes. Recall during prophase I, homologous chromosomes line up in pairs, gene-for-gene down their entire length, forming a configuration with four chromatids, known as a **tetrad**. At this point, the chromatids are very close to each other and some material from two chromatids switch chromosomes, that is, the material breaks off and reattaches at the same position on the homologous chromosome (**Figure** 6.13). This exchange of genetic material can happen many times within the same pair of homologous chromosomes, creating unique combinations of genes. This process is also known as **recombination**.

As mentioned above, in humans there are over 8 million configurations in which the chromosomes can line up during metaphase I. It is the specific processes of meiosis, resulting in four unique haploid cells, that results in these many combinations. **Figure** 6.14 compares mitosis and meiosis. This independent assortment, in which the chromosome inherited from either the father or mother can sort into any gamete, produces the potential for tremendous genetic variation. Together with random fertilization, more possibilities for genetic variation exist between any two people than individuals alive today. Sexual reproduction is the random fertilization of a gamete from the female using a gamete from the male. In humans, over 8 million (2^{23}) chromosome combinations exist in the production of gametes in both the male and female. A sperm cell, with over 8 million chromosome combinations, fertilizes an egg

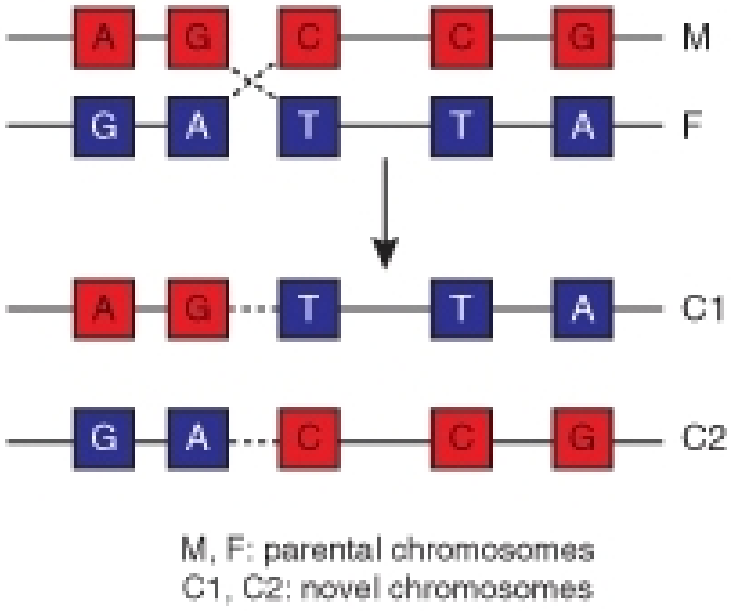

Figure 6.13: Crossing-over. A maternal strand of DNA is shown in red. Paternal strand of DNA is shown in blue. Crossing over produces two chromosomes that have not previously existed. The process of recombination involves the breakage and rejoining of parental chromosomes (M, F). This results in the generation of novel chromosomes (C1, C2) that share DNA from both parents.

cell, which also has over 8 million chromosome combinations. That is over 64 trillion unique combinations, not counting the unique combinations produced by crossing-over. In other words, each human couple could produce a child with over 64 trillion unique chromosome combinations.

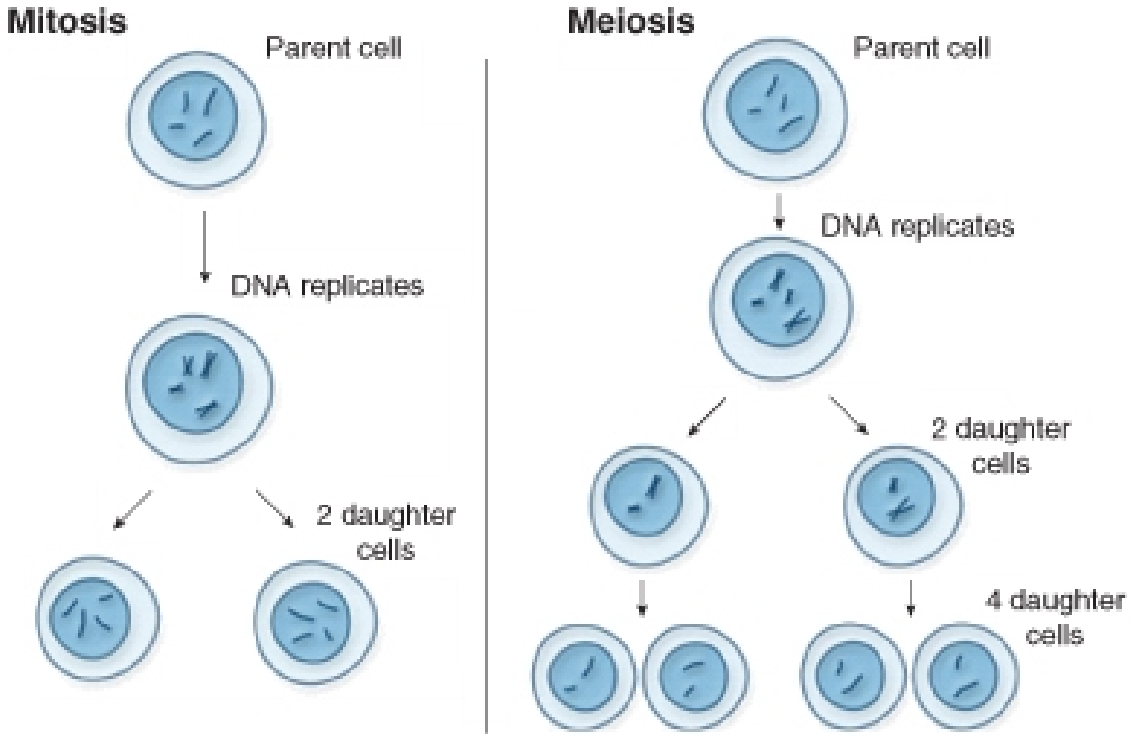

Figure 6.14: Mitosis vs. Meiosis Comparison. Mitosis produces two diploid daughter cells, genetically identical to the parent cell. Meiosis produces four haploid daughter cells, each genetically unique. See for an animation comparing the two processes.

Gametogenesis

At the end of meiosis, haploid cells are produced. These cells need to further develop into mature gametes capable of fertilization, a process called **gametogenesis** (**Figure** 6.15). Gametogenesis differs between the sexes. In the male, the production of mature sperm cells, or **spermatogenesis**, results in four haploid gametes, whereas, in the female, the production of a mature egg cell, **oogenesis**, results in just one mature gamete.

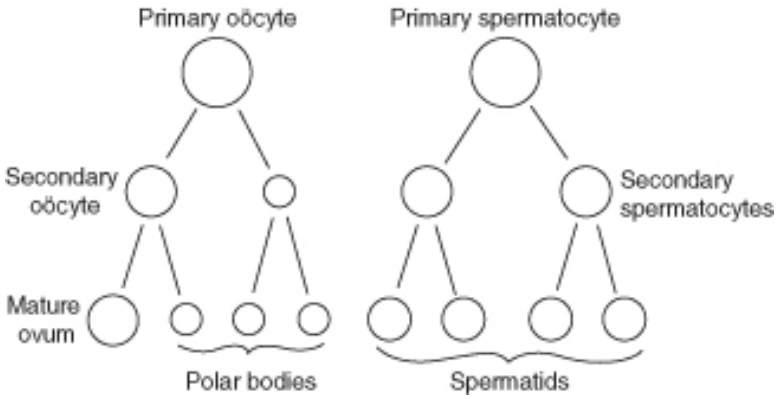

Figure 6.15: Analogies in the process of maturation of the ovum and the development of the spermatids. Four haploid spermatids form during meiosis from the primary spermatocyte, whereas only 1 mature ovum, or egg forms during meiosis from the primary oocyte. Three polar bodies may form during oogenesis. These polar bodies will not form mature gametes.

During spermatogenesis, primary spermatocytes go through the first cell division of meiosis to produce secondary spermatocytes. These are haploid cells. Secondary spermatocytes then quickly complete the meiotic division to become spermatids, which are also haploid cells. The four haploid cells produced from meiosis develop a flagellum tail and compact head piece to become mature sperm cells, capable of swimming and fertilizing an egg. The compact head, which has lost most of its cytoplasm, is key in the formation of a streamlined shape. The middle piece of the sperm, connecting the head to the tail, contains many mitochondria, providing energy to the cell. The sperm cell essentially contributes only DNA to the zygote.

On the other hand, the egg provides the other half of the DNA, but also organelles, building blocks for compounds such as proteins and nucleic acids, and other necessary materials. The egg, being much larger than a sperm cell, contains almost all of the cytoplasm a developing embryo will have during its first few days of life. Therefore, oogenesis is a much more complicated process than spermatogenesis.

Oogenesis begins before birth and is not completed until after fertilization. Oogenesis begins when an oogonia (singular, oogonium), which are the immature eggs that form in the ovaries before birth, with the diploid number of chromosomes undergoes mitosis to form primary oocytes, also with the diploid number. It proceeds as a primary oocyte undergoes the first cell division of meiosis to form secondary oocytes with the haploid number of chromosomes. A secondary oocyte undergoes the second meiotic cell division to form a haploid ovum if it is fertilized by a sperm. The one egg cell that results from meiosis contains most of the cytoplasm, nutrients, and organelles. This unequal distribution of materials produces one large cell, and one cell with little more than DNA. This other cell, known as a **polar body**, eventually breaks down. The larger cell undergoes meiosis II, once again producing a large cell and a polar body. The large cell develops into the mature gamete, called an ovum.

Sexual Life Cycles

Eukaryotes have three different versions of the sexual life cycle: a haploid life cycle, a diploid life cycle, and a life cycle known as the alternation of generations (**Figure** 6.16). A **life cycle** is the span in the life of an organism from one generation to the next. All species that reproduce sexually follow a basic pattern, alternating between haploid and diploid chromosome numbers. The sexual life cycle depends on when meiosis occurs and the type of cell that undergoes meiosis.

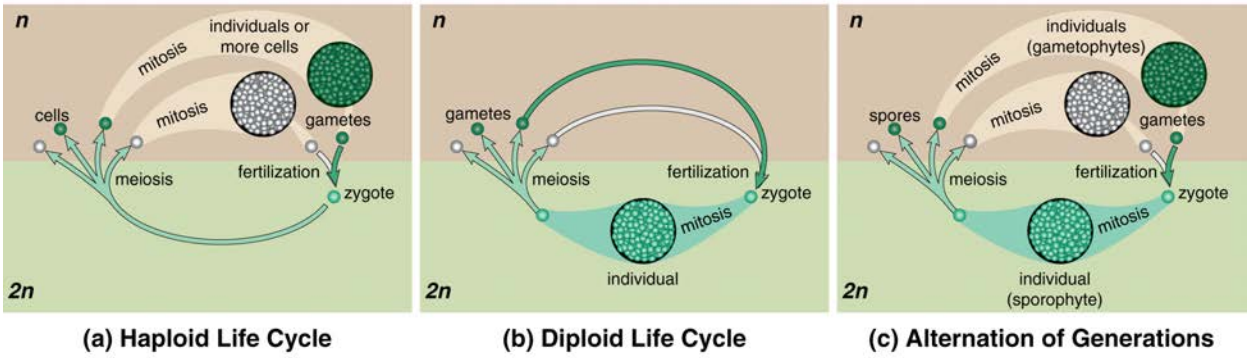

Figure 6.16: Sexual Life Cycles.

Haploid Life Cycles

The haploid life cycle is the simplest life cycle. Organisms with this life cycle, such as many protists and some fungi and algae, spend the majority of their life cycle as a haploid cell. In fact, the zygote is the only diploid cell. The zygote immediately undergoes meiosis, producing four haploid cells, which grow into haploid multicellular organisms. These organisms produce gametes by mitosis. The gametes fuse through a process called fusion to produce diploid zygotes which undergo meiosis, continuing the life cycle.

Diploid Life Cycles

Organisms that have a diploid life cycle spend the majority of their lives as diploid adults. All diploid adults inherit half of their DNA from each parent. When they are ready to reproduce, diploid reproductive cells undergo meiosis and produce haploid gametes. These gametes then fuse through fertilization and produce a diploid zygote, which immediately enters G_1 of the cell cycle. Next, the zygote's DNA is replicated. Finally, the processes of mitosis and cytokinesis produce two genetically identical diploid cells. Through repeated rounds of growth and division, this organism becomes a diploid adult and the cycle continues.

Alternation of Generations

Plants, algae, and some protists have a life cycle that alternates between diploid and haploid phases, known as alternation of generations. In plants, the life cycle alternates between the diploid sporophyte and haploid gametophyte. Spore forming cells in the diploid sporophyte undergo meiosis to produce **spores**, a haploid reproductive cell. Spores can develop into an adult without fusing with another cell. The spores give rise to a multicellular haploid gametophyte, which produce gametes by mitosis. The gametes fuse, producing a diploid zygote, which grow into the diploid sporophyte.

Lesson Summary

- Asexual reproduction produces a clone, an organism that is genetically identical to its parent.
- Asexual reproduction includes fission, fragmentation and budding.
- Sexual reproduction involves haploid gametes and produces a diploid zygote through fertilization.
- Meiosis is a type of cell division that halves the number of chromosomes. There are eight stages of meiosis, divided into meiosis I and meiosis II. DNA is not replicated between meiosis I and meiosis II.
- Crossing-over, the independent assortment of chromosomes during anaphase I, and random fertilization result in genetic variation.
- Meiosis is a step during spermatogenesis and oogenesis. Spermatogenesis produces four haploid sperm cells, while oogenesis produces one mature ovum.
- Eukaryotes have three different versions of the sexual life cycle: a haploid life cycle, a diploid life cycle, and a life cycle known as the alternation of generations. The sexual life cycle depends on when meiosis occurs and the type of cell that undergoes meiosis.

Review Questions

1. Define crossing-over in meiosis.
2. Describe how crossing-over, independent assortment, and random fertilization lead to genetic variation.
3. Compare and contrast mitosis and meiosis.
4. List the main differences between asexual and sexual reproduction.
5. How many chromosomes does a diploid human cell have? How many chromosomes does a haploid human cell have?
6. Name the three different sexual life cycles. What characterizes the differences between these life cycles?
7. Compare binary fission and asexual reproduction.

Further Reading / Supplemental Links

- http://www.genome.gov
- http://www.accessexcellence.org/RC/VL/GG/meiosis.html
- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/M/Meiosis.html
- http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookmeiosis.html

Vocabulary

alternation of generations A life cycle that alternates between diploid and haploid phases.

asexual reproduction Reproduction without gametes; the simplest and most primitive method of reproduction; produces a clone, an organism that is genetically identical to its parent.

budding Asexual reproduction in which new individuals split off from existing ones; the bud may stay attached or break free from the parent.

crossing-over The exchange of genetic material between non-sister chromatids of homologous chromosomes; also known as recombination.

diploid A cell containing two sets of chromosomes; in human cells, two sets contains 46 chromosomes.

fertilization The joining of gametes during reproduction.

fission Asexual reproduction in which a parent separates into two or more individuals of about equal size.

fragmentation Asexual reproduction in which the body breaks into several fragments, which later develop into complete adults.

gametes An organism's reproductive cells, such as sperm and egg cells.

gametogenesis The further maturation of the haploid cells produced by meiosis into mature gametes capable of fertilization.

gametophyte Produces gametes by mitosis; in alternation of generation life cycles.

haploid A cell containing one set of chromosomes; in human gametes, one set is 23 chromosomes.

life cycle The span in the life of an organism from one generation to the next.

meiosis A type of cell division that halves the number of chromosomes.

oogenesis The production of a mature egg cell; results in just one mature ovum, or egg cell.

polar body Cell formed during oogenesis; contains little cytoplasm and eventually breaks down; does not form a gamete.

sexual reproduction Reproduction involving the joining of haploid gametes, producing genetically diverse individuals.

spermatogenesis The production of mature sperm cells; results in four haploid gametes.

spore A haploid reproductive cell; found in plants, algae and some protists; can develop into an adult without fusing with another cell.

tetrad A configuration with four chromatids; formed by the pairing of homologous chromosomes during prophase I of meiosis.

Points to Consider

- The next unit, Genetics, discusses the branch of biology that studies heredity. What is heredity?
- What role do you think meiosis plays in heredity?
- Describe what would happen if gametes were formed by mitosis.
- Human Genetics is an ever increasingly important field of medicine. Explain why this field of medicine is so important.

Image Sources

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(5) http://commons.wikimedia.org/wiki/File:Sexual_cycle.svg. GNU-FDL.

(6) CK-12 Foundation. http://en.wikipedia.org/wiki/Image:Chromosomal_Recombination.svg. CC-BY 2.5.

(7) Marek Kultys. http://en.wikipedia.org/wiki/File:Meiosis_diagram.jpg. CC-BY-SA.

(8) *Magnification of a budding yeast.*. Public Domain.

(9) http://en.wikipedia.org/wiki/File:Condensed_Eukaryotic_Chromosome.png. GNU-FDL.

(10) USNLM. http://ghr.nlm.nih.gov/handbook/illustrations/mitosismeiosis. Public Domain.

(11) http://en.wikipedia.org/wiki/Image:Binary_fission.png. CC-BY-SA 3.0.

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(15) NCBI. http://en.wikipedia.org/wiki/Image:MajorEventsInMitosis.jpg. Public Domain.

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Chapter 7

Mendelian Genetics

7.1 Lesson 7.1: Mendel's Investigations

Lesson Objectives

- Identify how Mendel's study of science and math was important to his success in research.
- Distinguish between characteristics and traits.
- Explain how Mendel was able to control pollination of the pea plants.
- Identify the terms used to describe the three generations in Mendel's studies.
- State one reason for carrying out a monohybrid cross.
- Identify the traits that appeared in Mendel's F_2 generation.
- Identify the actions of dominant alleles and recessive alleles for a trait.
- Outline the Law of Segregation.
- Outline the Law of Independent Assortment.
- Explain Mendel's results in relation to genes and chromosomes.
- Distinguish between genotype and phenotype.

Introduction

For thousands of years, humans have understood that characteristics such as eye color or flower color are passed from one generation to the next. The passing of characteristics from parent to offspring is called **heredity**. Humans have long been interested in understanding heredity. Many hereditary mechanisms were developed by scholars but were not properly tested or quantified. The scientific study of genetics did not begin until the late 19th century. In experiments with garden peas, Austrian monk Gregor Mendel described the patterns of inheritance.

Gregor Mendel: Teacher and Scientist

Gregor Johann Mendel was an Augustinian monk, a teacher, and a scientist (**Figure** 7.1). He is often called the "father of modern genetics" for his study of the inheritance of traits in pea plants. Mendel showed that the inheritance of traits follows particular laws, which were later named after him. The significance of Mendel's work was not recognized until the turn of the 20th century. The rediscovery of his work led the foundation for the era of modern **genetics**, the branch of biology that focuses on heredity in organisms.

Figure 7.1: Gregor Johann Mendel "The Father of Modern Genetics." 1822-1884.

Johann Mendel was born in 1822 and grew up on his parents' farm in an area of Austria that is now in the Czech Republic. He overcame financial hardship and ill health to excel in school. In 1843 he entered the Augustinian Abbey in Brünn (now Brno, Czech Republic.) Upon entering monastic life, he took the name Gregor. While at the monastery, Mendel also attended lectures on the growing of fruit and agriculture at the Brünn Philosophical Institute. In 1849 he accepted a teaching job, but a year later he failed the state teaching examination. One of his examiners recommended that he be sent to university for further studies. In 1851 he was sent to the University of Vienna to study natural science and mathematics. Mendel's time at Vienna was very important in his development as a scientist. His professors encouraged him to learn science through experimentation and to use mathematics to help explain observations of natural events. He returned to Brünn in 1854 as a natural history and physics teacher.

Mendel's Experiments

In 1853 and 1854, Mendal published two papers on crop damage by insects. However, he is best known for his later studies of the pea plant *Pisum sativum*. Mendel was inspired by both his professors at university and his colleagues at the monastery to study variation in plants. He had carried out artificial fertilization on plants many times in order to grow a plant with a new color or seed shape. **Artificial fertilization** is the process of transferring pollen from the male part of the flower to the female part of another flower. Artificial fertilization is done in order to have seeds that will grow into plants that have a desired trait, such as yellow flowers.

During Mendel's time, the popular **blending inheritance** hypothesis stated that offspring were a "mix" of their parents. For example, if a pea plant had one short parent and one tall parent, that pea plant would be of medium height. It was believed that the offspring would then pass on heritable units, or factors, for medium sized offspring. (Today we know these heritable units are genes; however, Mendel did not know of the concept of a gene.) Mendel noted that plants in the monastery gardens sometimes gave rise to plants that were not exactly like the parent plants, nor were they a "mix" of the parents. He also noted that certain traits reappeared after "disappearing" in an earlier generation. Mendel was interested in finding out if there was a predictable pattern to the inheritance of traits. Between 1856 and 1863 he grew and tested about 29,000 pea plants in the monastery garden.

Mendel may have chosen to study peas because they are fast-growing plants that are available in different varieties. For example, one variety of pea plant has purple flowers, as shown in **Figure** 7.2, while another variety has white flowers.

Mendel chose to study seven characteristics of pea plants. A **characteristic** is a heritable feature, such as flower color. Each characteristic Mendel chose to study occurred in two contrasting traits. A **trait** is a heritable variant of a characteristic, such as purple or white flower color. Table 7.1 lists the seven characteristics Mendel studied, and their two contrasting traits.

Table 7.1: **The Seven Characteristics Mendel Studied and Their Contrasting Traits**

Flower Color	Flower Position on Stem	Stem Length	Pod Shape	Pod Color	Seed Shape	Seed Color
violet-red (purple)	axial	tall	inflated	green	round	green
white	terminal	short	constricted	yellow	wrinkled	yellow

Figure 7.2: the pea plant species that Mendel studied.

Pea Plant Pollination

In order to study these characteristics, Mendel needed to control the pollination of the pea plants. Pollination occurs when the pollen from the male reproductive part of a flower, called the anthers, is transferred to the female reproductive part of a flower, called the stigma. Pea plants are **self-pollinating**, which means the pollen from a flower on a single plant transfers to the stigma of the same flower or another flower on the same plant. In order to avoid self-pollination, Mendel removed the anthers from the flowers on a plant. He then carefully transferred pollen from the anthers of another plant and dusted the pollen onto the stamen of the flowers that lacked anthers. This process caused cross-pollination. **Cross-pollination** occurs when pollen from one flower pollinates a flower on a different plant. In this way, Mendel controlled the characteristics that were passed onto the offspring. **Figure** 7.3 shows the location of the male and female parts of *P. sativum*.

Mendel's First Experiment

Mendel began his studies by growing plants that were true-breeding for a particular trait. A **true-breeding** plant will always produce offspring with that trait when they self-pollinate. For example, a true-breeding plant with yellow seeds will always have offspring that have yellow seeds. In his first experiment, Mendel cross-pollinated two true-breeding plants of contrasting traits, such as purple and white flowered plants. The true-breeding parent plants are referred to as the **P generation** (parental generation). The hybrid offspring of the P

Figure 7.3: The location of the anthers in the pea flower. The anthers are illustrated alone in the image to the left of the transected flower (at right). Mendel controlled pollination of the plants by removing the immature anthers of certain plants.

generation are called the **F_1 generation** (filial generation). The hybrid offspring of the F_1 generation are called the F_2 generation (filial generation).

Monohybrid Crosses

Mendel first worked with plants that differed in a single characteristic, such as flower color. A hybridization is a cross between two individuals that have different traits. A hybridization in which only one characteristic is examined is called a **monohybrid cross**. The offspring of such a cross are called **monohybrids**. Mendel noted that hybridizing true-breeding (P-generation) plants gave rise to an F_1 generation that showed only one trait of a characteristic. For example, a true-breeding purple-flowering plant crossed with a true-breeding white-flowering plant always gave rise to purple-flowered hybrid plants. There were no white-flowered hybrids! Mendel wanted to know what happened to the white-flowered plants' "heritable factors." If indeed the white-flower "heritable factor" had disappeared, all future offspring of the hybrids would be purple-flowered. To test this idea, Mendel let the F_1 generation plants self-pollinate and then planted the resulting seeds.

Mendel's Results

The F_2 generation plants that grew included white-flowered plants! Mendel noted the ratio of white flowered plants to purple-flowered plants was about 3:1. That is, for every three purple-flowered plants, there was one white flowered plant. **Figure** 7.4 shows Mendel's results for the characteristic of flower color.

Mendel carried out identical studies over three generations, (P, F_1, and F_2), for the other six characteristics and found in each case that one trait "disappeared" in the F_1 generation, only to reappear in the F_2 generation. Mendel studied a large number of plants, as shown in **Table** 7.2, so he was confident that the ratios of different traits in the F_2 generation were representative.

Table 7.2: **Results of F1 Generation Crosses for Seven Characteristics in *P. sativum***

Characteristic	Dominant Trait	Recessive Trait	F2 Generation Dominant:Recessive	Ratio
Flower color	Purple	White	705:224	3.15:1
Flower position on stem	Axial	Terminal	651:207	3.14:1
Stem length	Tall	Short	787:277	2.84:1
Pod shape	Inflated	Constricted	882:299	2.95:1

Table 7.2: (continued)

Characteristic	Dominant Trait	Recessive Trait	F2 Generation Dominant:Recessive	Ratio
Pod color	Green	Yellow	428:152	2.82:1
Seed shape	Round	Wrinkled or angular	5474:1850	2.96:1
Seed color	Yellow	Green	6022:2001	3.01:1

Mendel's Theory of Heredity

Based on his observations, Mendel developed four hypotheses. These hypotheses are known as Mendel's theory of heredity. The hypotheses explain a simple form of inheritance in which two alleles of a gene are inherited to result in one of several traits in offspring. In modern terms, these hypotheses are:

1. **There are different versions of genes**. These different versions account for variations in characteristics. Different versions of a gene are called **alleles.** For example, there is a "yellow-pod" allele and a "green pod" allele. The blending inheritance hypothesis was discredited by Mendel's allele hypothesis.
2. **When two different alleles are inherited together, one may be expressed, while the effect of the other may be "silenced."** In the case of pod color, the allele for green pods is always expressed and is **dominant**. The allele for yellow pods, which is not expressed, is **recessive**. For instance, if a plant inherits a "yellow-pod" gene and a "green pod" gene, it will have only green pods.
3. **For each characteristic, an organism inherits two alleles, one from each parent**. Mendel noted that offspring could inherit their traits from either parent. In the case of the expressed trait, it did not matter whether it was the male gamete or female gamete that supplied the gene.
4. **When gametes are formed, the two alleles of each gene are separated** (**Figure** 7.5). During meiosis, each male or female gamete receives one allele for a trait. When the male and female gametes are fused at fertilization, the resulting zygote contains two alleles of each gene.

Random Segregation of Alleles

The **Law of Segregation** states that a pair of alleles is separated, or segregated, during the formation of gametes. During meiosis, homologous chromosomes are randomly separated. Each resulting gamete has an equal probability or chance of receiving either of the two alleles.

Table 2 :The Three Generations of Mendel's Experiments

P - generation		F_1 Generation hybrids all purple		F_2 Generation 705 purple and 224 white(A ratio of 3.15:1)
				
×	Cross-pollination		Self-pollination	
				
				

Figure 7.4

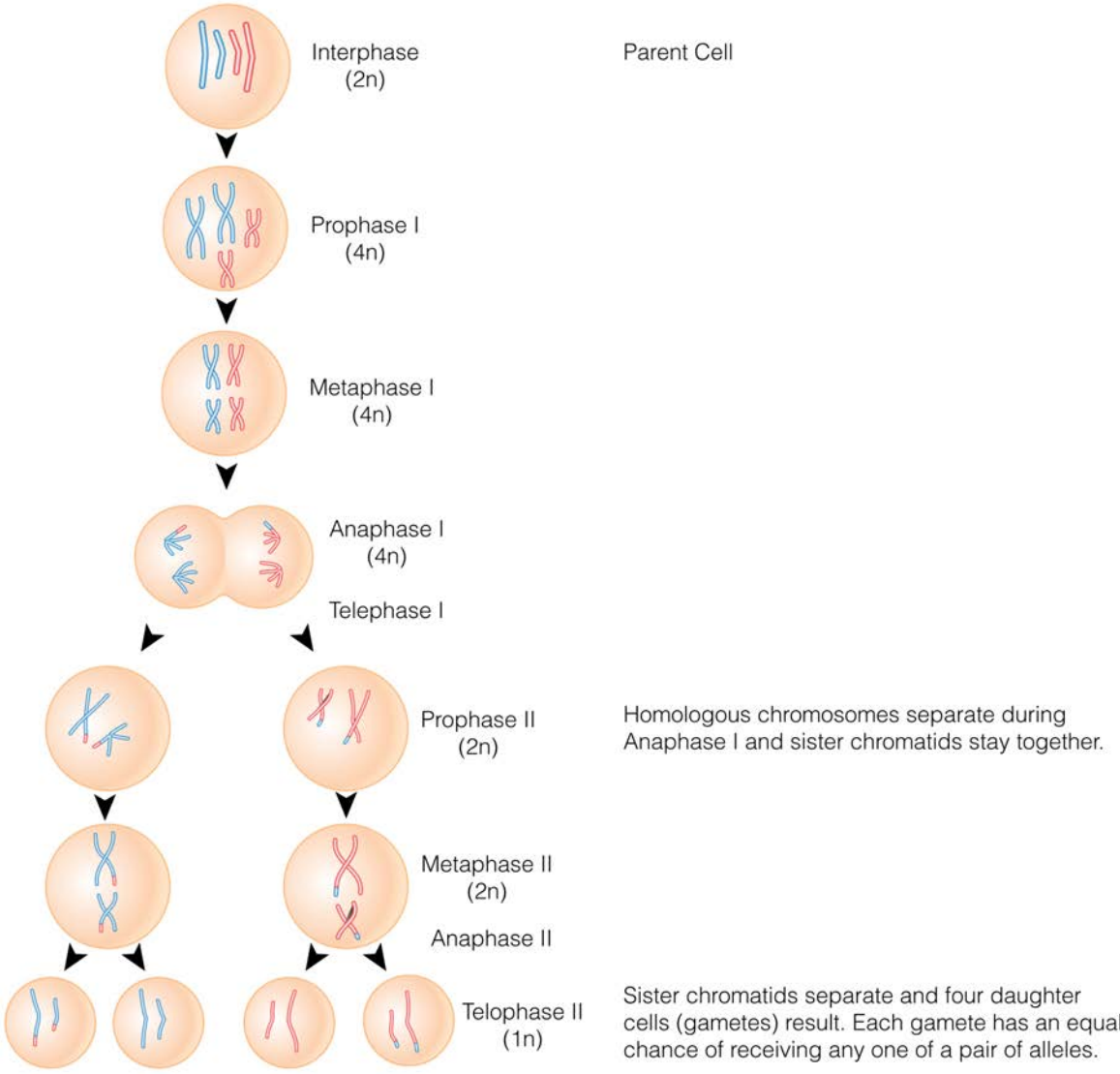

Figure 7.5: Alleles on homologous chromosomes are randomly separated during gamete formation. Upon fertilization, the fusion of a male and female gametes results in new combinations of alleles in the resulting zygote.

Mendel's Second Experiment

Mendel also crossed pea plants that differed in two characteristics, such as seed color and shape. A **dihybrid cross** is a cross in which the inheritance of two characteristics are tracked at the same time. The offspring of such a cross are called **dihybrids**. Mendel wanted to see if the inheritance of characteristics were dependent. He concluded that characteristics were inherited independently of each other.

The Law of Independent Assortment

The **Law of Independent Assortment**, also known as or Mendel's Second Law, states that the inheritance of one trait will not affect the inheritance of another. Mendel concluded that different traits are inherited independently of each other, so that there is no relationship, for example, between seed color and seed shape. In modern terms, alleles of each gene separate independently during gamete formation.

Linked Genes on Chromosomes

We now know that the only alleles that are inherited independently are ones that are located far apart on a chromosome or that are on different chromosomes. There are many genes that are close together on a chromosome, and are packaged into the gametes together. Genes that are inherited in this way are called **linked genes**. Linked genes tend to be inherited together because they are located on the same chromosome. Genetic linkage was first discovered by the British geneticists William Bateson and Reginald Punnett shortly after Mendel's laws were rediscovered.

Mendelian Theory and Molecular Genetics

Mendel was perhaps lucky in that the characteristics he chose to study in the pea plants had a relatively simple pattern of inheritance. These characteristics were determined by one gene for which there were exactly two alleles. One of these alleles was dominant and the other recessive. Had any of these characteristics been determined by more than one gene, he may not have been able to develop such amazing insight into inheritance. In many instances, the relationship between genes and inheritance is more complex than that which Mendel found. Nevertheless, geneticists have since found that Mendel's findings can be applied to many organisms. For example, there are clear patterns of Mendelian inheritance in humans. Albinism (**Figure** 7.6), is a genetic disorder that is inherited as a simple Mendelian trait.

Figure 7.6: Albinism is a recessively inherited disorder in which the body does not produce enough of the pigment melanin. The skin, hair, and eyes of a person with albinism appear white or pale.

Dominant and Recessive Alleles

Mendel used letters to represent dominant and recessive factors. Likewise, geneticists now use letters to represent alleles. Capital letters refer to dominant alleles, and lowercase letters refer to recessive alleles. For example, the dominant allele for the trait of green pod color is indicated by G. The recessive trait of yellow pod color is indicated by g. A true-breeding plant for green pod color would have identical alleles GG in all its somatic cells. Likewise, a true-breeding plant for yellow pod color would have identical alleles gg in all of its somatic cells. During gamete formation, each gamete receives one copy of an allele. When fertilization occurs between these plants, the offspring receives two copies of the allele, one from each parent. In this case, all of the offspring would have two different alleles, Gg, one from each of its parents.

An organism that has an identical pair of alleles for a trait is called **homozygous**. The true-breeding parents GG and gg are homozygous for the pod color gene. Organisms that have two different alleles for a gene are called **heterozygous**. The offspring of the cross between the GG and gg plants are all heterozygous for the pod color gene. Due to dominance and recessiveness of alleles, an organism's traits do not always reveal its genetics. Therefore, geneticists distinguish between an organism's genetic makeup, called its **genotype**, and its physical traits, called its **phenotype**. For example, the GG parent and the Gg offspring have the same phenotype (green pods) but different genotypes.

Lesson Summary

- Genetics is the branch of biology that focuses on heredity in organisms.
- Modern genetics is based on Mendel's explanation of how traits are passed from generation to generation.
- Mendel's use of mathematics in his pea plant studies was important to the confidence he had in his results.
- Mendel carried out his first experiments with true-breeding plants and continued them over a span of three generations.
- For each of the seven characteristics Mendel studied, he observed a similar ratio in the inheritance of dominant to recessive traits (3:1) in the F_2 generation.
- Mendel developed a theory that explained simple patterns of inheritance in which two alleles are inherited to result in one of several traits in offspring.
- The law of segregation states that a pair of alleles is segregated during the formation of gametes and that each gamete has an equal chance of getting either one of the allele.
- The law of independent assortment states that the inheritance of one trait will not affect the inheritance of another. That is, genes are inherited independently of each other.
- Linked genes are genes that are close together on the same chromosome. Linked genes are inherited together.
- Mendelian inheritance patterns can be seen in humans. Albinism is a genetic disorder that is inherited as a simple Mendelian trait.
- Genotype determines phenotype. A homozygous dominant or a heterozygous genotype will always show a dominant phenotype. A homozygous recessive genotype can only show a recessive phenotype.

Review Questions

1. Why was Mendel's understanding of mathematics and science important for his research?
2. What did Gregor Mendel contribute to the science of genetics?
3. What is a true-breeding plant?
4. How was Mendel able to control the pollination of his pea plants?
5. How does cross-pollination differ from self-pollination?
6. How did the appearance of Mendel's F_1 generation differ from the appearance of the P generation?
7. Identify the relationship between genes and alleles.
8. Summarize the law of segregation.
9. Summarize the law of independent assortment.
10. Relate the term homozygous to heterozygous by using an example from Mendel's experiments.
11. Relate the term genotype to phenotype by using an example from Mendel's experi-

ments.

12. Why can't you always identify the genotype of an organism from its phenotype?

Further Reading / Supplemental Links

- http://www.mendelweb.org/MWtime.html
- http://www1.umn.edu/ships/updates/mendel.htm
- http://www.macalester.edu/psychology/whathap/UBNRP/visionwebsite04/twotypes.html
- http://www.mendelweb.org
- http://www1.umn.edu/ships/updates/mendel2.htm
- http://anthro.palomar.edu/mendel/mendel_1.htm
- http://www.mendel-museum.org/eng/1online/experiment.html
- http://evolution.berkeley.edu/evosite/history/discretegenes.shtml
- http://en.wikipedia.org

Vocabulary

allele Different versions of a gene.

anther The male reproductive part of a flower.

artificial fertilization The process of transferring pollen from the male part of the flower to the female part of another flower; done in order to have seeds that will grow into plants that have a desired trait.

blending inheritance hypothesis Hypothesis that stated that offspring were a "mix" of their parents.

characteristic A heritable feature, such as flower color.

cross-pollination Fertilization in which pollen from one flower pollinates a flower on a different plant.

dihybrid cross A cross in which the inheritance of two characteristics are tracked at the same time.

dominant The allele that is expressed when two separate alleles are inherited.

F_1 generation The hybrid offspring of the P (parental) generation; first filial generation.

genetics The branch of biology that focuses on heredity in organisms.

genotype An organism's genetic makeup.

heredity The passing of characteristics from parent to offspring.

heterozygous Organisms that have two different alleles for a gene.

homozygous An organism that has an identical pair of alleles for a trait.

hybridization A cross between two individuals that have different traits.

Law of Independent Assortment States that the inheritance of one trait will not affect the inheritance of another.

Law of Segregation States that a pair of alleles is separated, or segregated, during the formation of gametes.

linked genes Genes that are close together on a chromosome, and are packaged into the gametes together.

monohybrid cross A hybridization in which only one characteristic is examined.

phenotype An organism's physical traits.

recessive The allele that is expressed only in the absence of a dominant allele.

self-pollinating Fertilization in which the pollen from a flower on a single plant transfers to the stigma of the same flower or another flower on the same plant.

stigma The female reproductive part of a flower.

trait A heritable variant of a characteristic, such as purple or white flower color.

true-breeding A plant that will always produce offspring with the parental trait when it self-pollinates.

Points to Consider

Next we will examine Mendelian Inheritance in further detail.

- Do you think all inheritance is as straightforward as the inheritance in pea plants?
- Is there a relationship between inheritance and probability? What might that relationship be?

7.2 Lesson 7.2: Mendelian Inheritance

Lesson Objectives

- Identify how probability is used to predict outcomes of genetic crosses.
- Outline how a Punnett Square helps predict outcomes of genetic crosses.
- Identify how probability can help determine the alleles in a gamete.
- Identify how a testcross is used to determine the genotype of an organism.
- Describe how monohybrid and dihybrid crosses differ.
- Identify the ratio of phenotypes that appeared in Mendel's dihybrid crosses.
- Examine how a pedigree is used in the study of human inheritance.
- Describe how codominance does not follow Mendelian Inheritance.
- Describe how incomplete dominance does not follow Mendelian Inheritance.
- Identify examples of polygenic traits in humans.
- Outline how heredity and environment can interact to affect phenotype.

Introduction

A **Mendelian trait** is a trait that is controlled by a single gene that has two alleles. One of these alleles is dominant and the other is recessive. Several inheritable conditions in humans are passed to offspring in a simple Mendelian fashion. Medical professionals use Mendel's laws to predict and understand the inheritance of certain traits in their patients. Also, farmers, animal breeders, and horticulturists who breed organisms can predict outcomes of crosses by understanding Mendelian inheritance.

Calculating Probability

The rules of probability that apply to tossing a coin or throwing a dice also apply to the laws of segregation and independent assortment. **Probability** is the likelihood that a certain event will occur. It is expressed by comparing the number of events that occur to the total number of possible events. The equation is written as:

Probability = (number of times an event is expected to occur/total number of times an event could happen)

For example, in Mendel's F_2 hybrid generation, the dominant trait of purple flower color appeared 705 times, and the recessive trait appeared 224 times. The dominant allele appeared 705 times out of a possible 929 times (705+224=929).

Probability = (705/929)

(705/929)= 0.76

Probability is normally expressed in a range between 0 and 1, but it can also be expressed as a percentage, fraction, or ratio. Expressed as a percentage, the probability that a plant of the F_2 generation will have purple flowers is 76%. Expressed as a fraction it is about ¾,and as a ratio it is roughly 3:1. The probability of the expression of the dominant allele for other characteristics can also be calculated the same way. In fact, Mendel found that all the other dominant "factors" had approximately a ¾ probability of being expressed in the F_2 hybrid generation. Review Table 7.1 for the results for the other six characteristics.

The probability the recessive trait will appear in the F_2 hybrid generation is calculated in the same way.

Probability = (224/929)

(224/929) = 0.24

The probability of the recessive trait appearing in the F_2 generation is 24% or about ¼.

Results predicted by probability are most accurate when many trials are done. The best way to illustrate this idea is to toss a coin. Because a coin has two sides, every time you toss it the chance of tossing heads or tossing tails is 50%. The outcome of each separate toss is unaffected by any previous or future result. For example, imagine you tossed seven heads in a row. You would think that the next toss is more likely to be a tail, but the possibility of tossing another head is still 50%. If you tossed the coin a total of ten times, a total of seven heads and three tails, you would calculate the probability of tossing heads is 70%. The fact that you carried out only a small number of trials has affected your results. If Mendel had grown only 10 plants, he would have gotten different probabilities for the appearance of dominant and recessive traits. However, Mendel carried out many thousands of trials. He was therefore sure that his results were due to probability, and not to chance.

Probability and the Law of Segregation

Each coin toss is a separate event. Likewise, gamete formation is a separate event. The probability that a Pp heterozygote produces gametes with a P allele or a p allele is 50% for each gamete cell. In a fertilization involving two such plants (as in the F_1 generation self-pollination experiment), each pollen cell and each egg cell have a 50% chance of having the P or p allele.

Predicting Genotypes with Punnett Squares

Mendel developed the law of segregation by following only a single characteristic, such as pod color, in his pea plants. Biologists use a diagram called a **Punnett Square**, to help predict the probable inheritance of alleles in different crosses. In a monohybrid cross, such as the one in **Figure** 7.7, the Punnett square shows every possible combination when combining one maternal (mother) allele with one paternal (father) allele. In this example, both organisms are heterozygous for flower color Pp (purple). Both plants produce gametes that contain both the P and p alleles. The probability of any single offspring showing the dominant trait is 3:1, or 75%.

Figure 7.7: A Punnett square helps determine the genotype of this heterozygous cross. Two pea plants, both heterozygous for flower color, are crossed. The offspring will show the dominant purple coloration in a 3:1 ratio. Or, about 75% of the offspring will be purple.

Using Probability to Determine Alleles in Gametes

In the monohybrid cross shown in **Figure** 7.7, two heterozygous plants are crossed. Both plants produce gametes, all of which contain either a P or p allele for flower color. The likelihood that any particular gamete contains the allele for a white flower can be calculated. Because a gamete can only carry one out of two alleles, there are only two possible outcomes

for a gamete. The probability that a gamete will carry the allele for white flower color is ½, 0.5, or 50%. The probability that a gamete will carry the allele for purple flower color is also ½.

Using Probability in a Heterozygous Cross

We can calculate the probability of any one of the offspring being heterozygous (Pp) or homozygous (PP or pp) for flower color. The probability of a plant inheriting the P or p allele from a heterozygous parent is ½. Multiply the probabilities of inheriting both alleles to find the probability that any one plant will be a pp homozygote.

½ × ½ = ¼ or 0.25

Only 25 %, or one outcome out of four, will result in a plant homozygous for white flower color (pp). The possibility that any one plant will be a PP homozygote is also 1/4. The heterozygous allele combination can happen twice (Pp or pP), so the two probabilities are added together ¼ + ¼ = 2/4, or ½. The probability that an offspring plant will be Pp heterozygous is ½.

Testcross and Punnett Squares

Suppose you have a purple and white flower and, as discussed above, purple color is dominant to white. The white flower must be homozygous for the recessive allele, but the genotype of the purple flower is unknown. It could be either PP or Pp. A testcross will determine the organism's genotype. In a **testcross**, the individual with the unknown genotype is crossed with a homozygous recessive individual (**Figure** 7.8). The unknown genotype can be determined by observing the phenotypes of the resulting offspring.

Dihybrid Crosses and Punnett Squares

Dihybrid crosses are more complicated than monohybrid crosses because more combinations of alleles are possible. For example, tracking the inheritance of seed color and pod color in a Punnett square requires that we track four alleles. G is the dominant allele for green pod color and g is the recessive allele for yellow pods. Y is the dominant allele for yellow seed color and y is the recessive allele for green seed color.

Two plants are crossed, one is true-breeding for green pods and yellow seeds (GGYY), the other is true-breeding for yellow pods and green seeds (ggyy). All of the F_1 generation will be heterozygous for both traits (GgYy). **Figure** 7.9, shows the dihybrid cross of the dihybrid P generation and the F_1 generation.

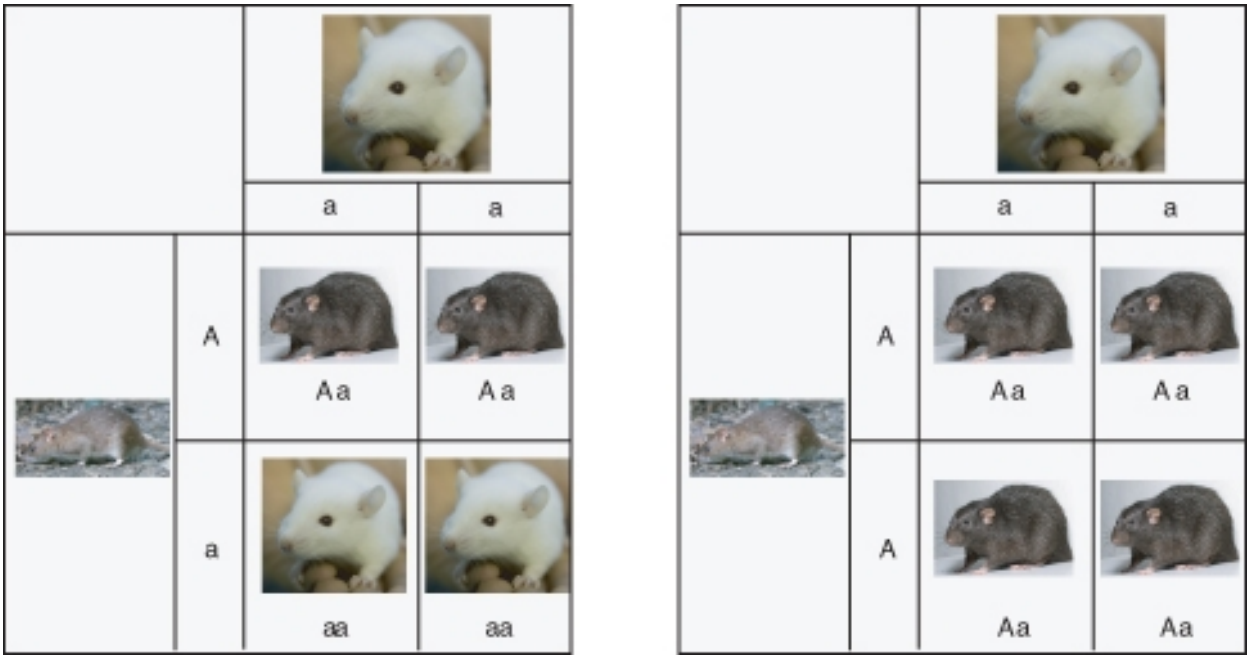

Figure 7.8: A testcross helps reveal the genotype of an organism when that organism shows the dominant trait, such as agouti coat color in rats. Such an organism could be homozygous dominant or heterozygous. Agouti is the common color of the Norway rat, .

Heterozygous Dihybrid Cross

In a dihybrid cross, four alleles can be inherited from any one parent at one time. When two heterozygous individuals are crossed, there are a total of 16 possible combinations of the four alleles. The phenotypes of the offspring with two independent traits show a 9:3:3:1 ratio. In a cross involving pea plants heterozygous for round, yellow seeds (GgYy), 9/16 plants have round, yellow seeds, 3/16 have round, green seeds, 3/16 have wrinkled, yellow seeds, and 1/16 has wrinkled, green seeds.

Mendelian Inheritance in Humans

A **pedigree** is a chart which shows the inheritance of a trait over several generations. A pedigree is commonly created for families, and it outlines the inheritance patterns of genetic disorders. **Figure** 7.10 shows a pedigree depicting recessive inheritance of a disorder through three generations. Scientists can tell the genetics of inheritance from studying a pedigree, such as whether the trait is sex-linked (on the X or Y chromosome) or autosomal (on a chromosome that does not determine sex), whether the trait is inherited in a dominant or recessive fashion, and possibly whether individuals with the trait are heterozygous or homozygous.

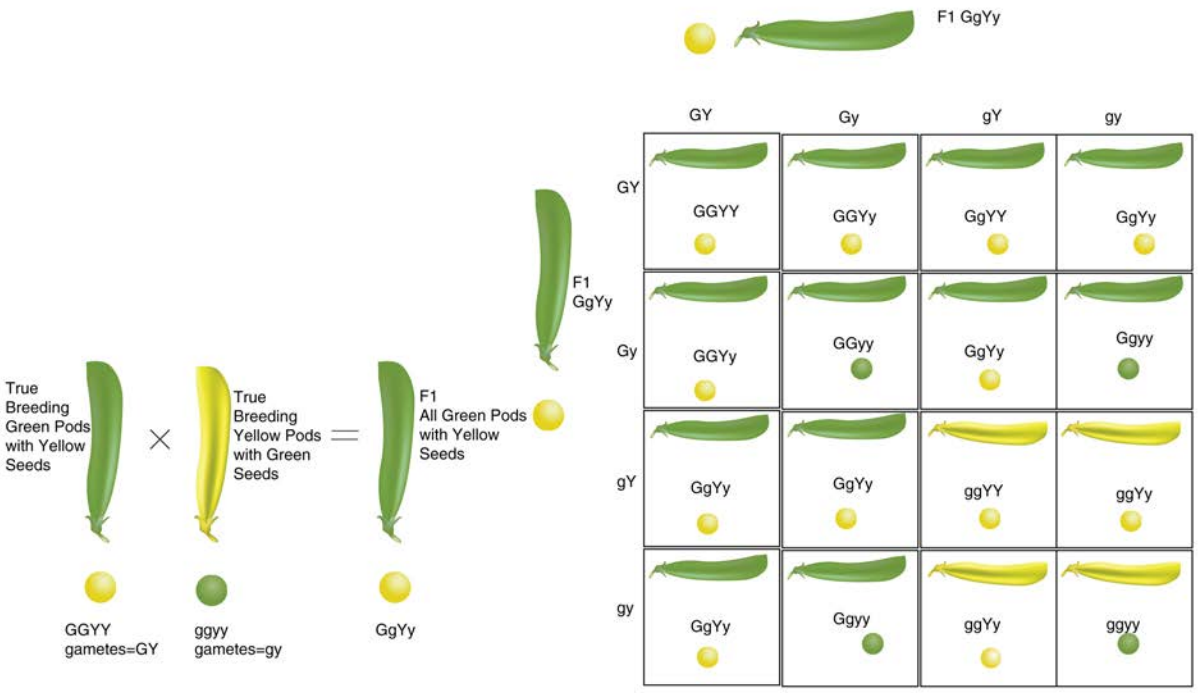

Figure 7.9: The dihybrid crosses were started by crossing two true-breeding plants, just as the monohybrid crosses were. The ratio of phenotypes (9:3:3:1) can be determined from the dihybrid Punnett square on the right. The genotype of the F generation can also be determined.

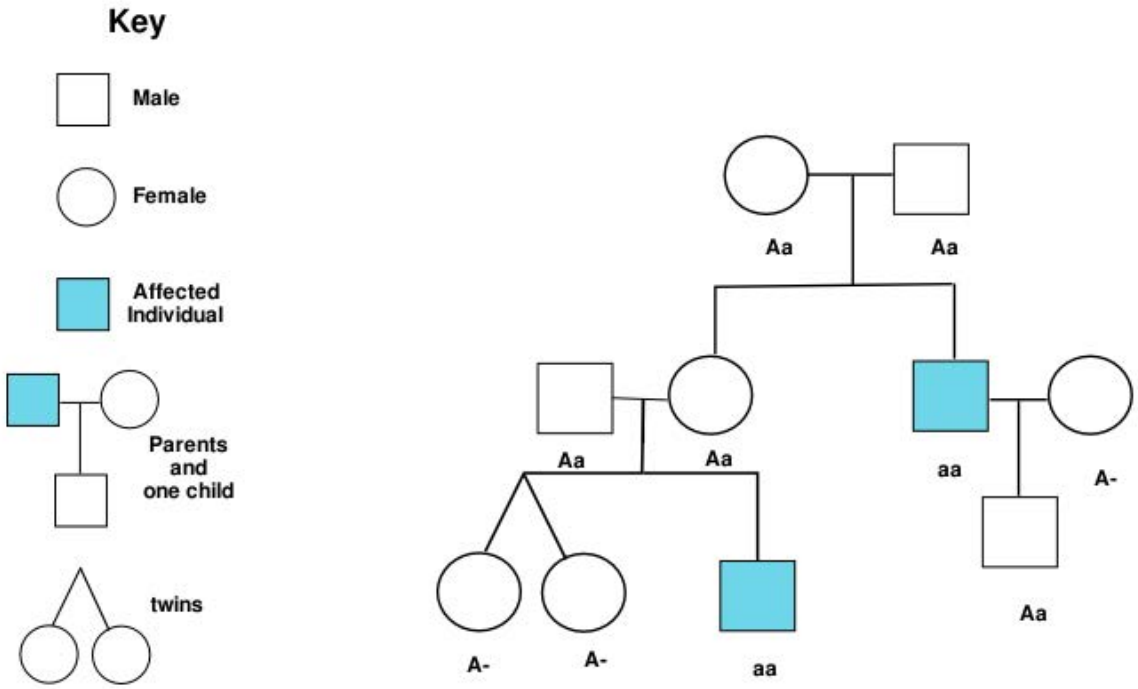

Figure 7.10: In a pedigree, squares symbolize males, and circles represent females. A horizontal line joining a male and female indicates that the couple had offspring. Vertical lines indicate offspring which are listed left to right, in order of birth. Shading of the circle or square indicates an individual who has the trait being traced. The inheritance of the recessive trait is being traced. A is the dominant allele and a is recessive.

Is the trait sex-linked or autosomal? A **sex chromosome** is a chromosome that determines the sex of an organism. Humans have two sex chromosomes, X and Y. Females have two X chromosomes (XX), and males have one X and one Y (XY). An **autosome** is any chromosome other than a sex chromosome. If a trait is autosomal it will affect males and females equally.

A **sex-linked trait** is a trait whose allele is found on a sex chromosome. The human X chromosome is significantly larger than the Y chromosome; there are many more genes located on the X chromosome than there are on the Y chromosome. As a result there are many more X-linked traits than there are Y-linked traits. Most sex-linked traits are recessive. Because males carry only one X chromosome, if they inherit a recessive sex-linked gene they will show a sex-linked condition.

Because of the recessive nature of most sex-linked traits, a female who shows a sex-linked condition would have to have two copies of the sex-linked allele, one on each of her X chromosomes. **Figure** 7.11 shows how red-green colorblindness, a sex-linked disorder, is passed from parent to offspring.

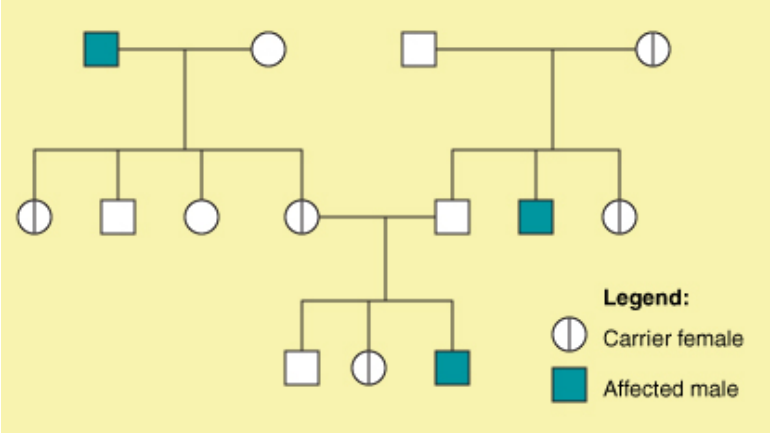

Figure 7.11: An X-linked disorder such as red-green colorblindness is normally passed onto the son of a carrier mother. Usually, females are unaffected as they have a second, normal copy of the allele on the second X chromosome. However, if a female inherits two defective copies of the allele, she will be colorblind. Therefore, every son of a colorblind woman will be colorblind.

Is the Trait Dominant or Recessive? If the trait is autosomal dominant, every person with the trait will have a parent with the trait. If the trait is recessive, a person with the trait may have one, both or neither parent with the trait. An example of an autosomal dominant disorder in humans is Huntington's disease (HD). Huntington's disease is a degenerative disease of the nervous system. It has no obvious effect on phenotype until the person is aged 35 to 45 years old. The disease is non-curable and, eventually, fatal. Every child born to a person who develops HD has a 50% chance of inheriting the defective allele from the parent.

Are the Individuals with the Trait Heterozygous or Homozygous? If a person is homozygous or heterozygous for the dominant allele of a trait, they will have that trait. If the person is heterozygous for a recessive allele of the trait, they will not show the trait. A person who is heterozygous for a recessive allele of a trait is called a **carrier**. Only people who are homozygous for a recessive allele of a trait will have the trait.

Non-Mendelian Modes of Inheritance

The relationship between genotype and phenotype is rarely as simple as the examples Mendel studied. Each characteristic he studied had two alleles, one of which was completely dominant and the other completely recessive. Geneticists now know that alleles can be codominant, or incompletely dominant.

Codominance

Codominance occurs when both traits appear in a heterozygous offspring. Neither allele is completely dominant nor completely recessive. For example, roan shorthorn cattle have codominant genes for hair color. The coat has both red and white hairs. The letter R indicates red hair color, and R' white hair color. In cases of codominance, the genotype of the organism can be determined from its phenotype. The heifer in **Figure** 7.12 is RR' heterozygous for coat color.

Figure 7.12: The roan coat of this shorthorn heifer is made up of red and white hairs. Both the red and white hair alleles are codominant. Therefore cattle with a roan coat are heterozygous for coat color (RR').

Incomplete Dominance

Incomplete dominance occurs when the phenotype of the offspring is somewhere in between the phenotypes of both parents; a completely dominant allele does not occur. For example, when red snapdragons (C^RC^R)</math> are crossed with white snapdragons (C^WC^W), the F_1 hybrids are all pink hetrozygotes for flower color (C^RC^W). The pink color is an intermediate between the two parent colors. When two F_1 (C^RC^W) hybrids are crossed they will produce red, pink, and white flowers. The genotype of an organism with incomplete dominance can be determined from its phenotype (**Figure** 7.13).

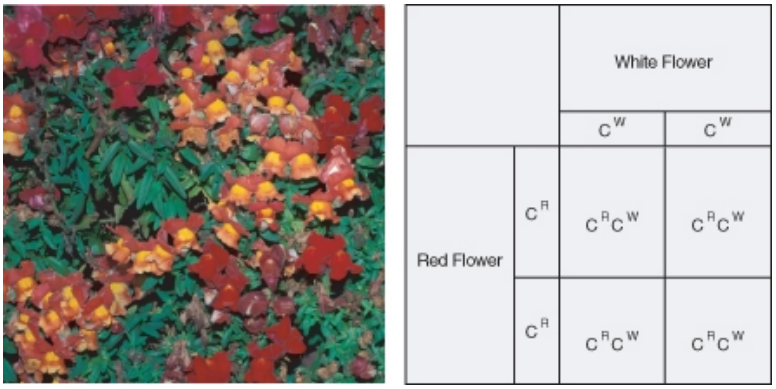

Figure 7.13: Snapdragons show incomplete dominance in the traits for flower color. The offspring of homozygous red-flowered and homozygous white-flowered parents are heterozygous pink-flowered.

Complex Forms of Heredity

Traits that are affected by more than one gene are called **polygenic traits**. The genes that affect a polygenic trait may be closely linked on a chromosome, unlinked on a chromosome, or on different chromosomes. Polygenic traits are often difficult for geneticists to track because the polygenic trait may have many alleles. Also, independent assortment ensures the genes combine differently in gametes. Therefore, many different intermediate phenotypes exist in offspring. Eye color (**Figure** 7.14), and skin color are examples of polygenic traits in humans.

When three or more alleles determine a trait, the trait is said to have **multiple alleles**. The human ABO blood group is controlled by a single gene with three alleles: i, I^A, I^B, and the recessive i allele. The gene encodes an enzyme that affects carbohydrates that are found on the surface of the red blood cell. A and B refer to two carbohydrates found on the surface of red blood cells. There is not an O carbohydrate. Type O red blood cells do not have either type A or B carbohydrates on their surface.

The alleles I^A and I^B are dominant over i. A person who is homozygous recessive ii has type

Figure 7.14: Eye color and skin color are examples of polygenic traits; they are influenced by more than one gene.

O blood. Homozygous dominant I^AI^A or heterozygous dominant I^Ai have type A blood, and homozygous dominant I^BI^B or heterozygous dominant I^Bi have type B blood. I^AI^B people have type AB blood, because the A and B alleles are codominant. Type A and type B parents can have a type AB child. Type A and a type B parent can also have a child with Type O blood, if they are both heterozygous (I^Bi,I^Ai). The table (7.3) shows how the different combinations of the blood group alleles can produce the four blood groups, A, AB, B, and O.

Table 7.3: **Bloodtype as Determined by Multiple Alleles**

	I^A	**I^B**	**i**
I^A	I^AI^A TYPE A	I^AI^B TYPE AB	I^Ai TYPE A
I^B	I^A I^B TYPE AB	I^B I^B TYPE B	I^B i TYPE B
i	i I^A TYPE A	i I^B TYPE B	ii TYPE O

Effects of Environment on Phenotype

Genes play an important part in influencing phenotype, but genes are not the only influence. Environmental conditions, such as temperature and availability of nutrients can affect phenotypes. For example, temperature affects coat color in Siamese cats.

The pointed pattern is a form of partial albinism, which results from a mutation in an enzyme that is involved in melanin production. The mutated enzyme is heat-sensitive; it fails to work at normal body temperatures. However, it is active in cooler areas of the skin. This results in dark coloration in the coolest parts of the cat's body, such as the lower limbs and the face, as shown in **Figure** 7.15. The cat's face is cooled by the passage of air through the nose. Generally adult Siamese cats living in warm climates have lighter coats than those in cooler climates.

Height in humans is influenced by many genes, but is also influenced by nutrition. A person who eats a diet poor in nutrients will not grow as tall as they would have had they eaten a more nutritious diet. Scientists often study the effects of environment on phenotype by

Figure 7.15: The dark "points," on this Siamese cat are caused by a gene that codes for a temperature-sensitive enzyme. The enzyme, which causes a darkening of the cat's fur, is active only in the cooler parts of the body such as the tail, feet, ears, and area around the nose.

Lesson Summary

- Probability is the likelihood that a certain event will occur. It is expressed by comparing the number of events that actually occur to the total number of possible events. Probability can be expressed as a fraction, decimal, or ratio.
- A Punnett square shows all the possible genotypes that can result from a given cross.
- A testcross examines the genotype of an organism that shows the dominant phenotype for a given trait. The heterozygous organism is crossed with an organism that is homozygous recessive for the same trait.
- A dihybrid cross-examines the inheritance of two traits at the same time.
- A pedigree can help geneticists discover if a trait is sex-linked, if it is dominant or recessive, and if the person (or people) who have the trait are homozygous or heterozygous for that trait.
- The Mendelian pattern of inheritance and expression does not apply to all traits. Codominant traits, incompletely dominant traits, and polygenic traits do not follow simple Mendelian patterns of inheritance. Their inheritance patterns are more complex.
- An organism's phenotype can be influenced by environmental conditions.

Review Questions

1. What does the probability equation help to determine?
2. How can probability be expressed?
3. Outline how Punnett squares are useful.
4. Identify the purpose of a testcross.
5. How do the Punnett squares for a monohybrid cross and a dihybrid cross differ?
6. Mendel carried out a dihybrid cross to examine the inheritance of the characteristics for seed color and seed shape. The dominant allele for yellow seed color is Y, and the recessive allele for green color is y. The dominant allele for round seeds is R, and the recessive allele for a wrinkled shape is r. The two plants that were crossed were F1 dihybrids RrYy. Identify the ratios of traits that Mendel observed in the F2 generation, and explain in terms of genotype what each number means. Create a Punnett square to help you answer the question.
7. Draw a pedigree that illustrates the passing of the dominant cleft chin trait through three generations. A person who has two recessive alleles does not have a cleft chin. Let us say that C is the dominant allele, c is the recessive allele.
8. A classmate tells you that a person can have type AO blood. Do you agree? Explain.
9. Mendelian inheritance does not apply to the inheritance of alleles that result in incomplete dominance and codominance. Explain why this is so.
10. Outline the relationship between environment and phenotype.

Further Reading / Supplemental Links

- http://www.nbii.gov/portal/server.pt?open=512&objID=405&PageID=581&mode=2&in_hi_userid=2&cached=true
- http://omia.angis.org.au/retrieve.shtml?pid=417
- http://www.curiosityrats.com/genetics.html
- http://www.macalester.edu/psychology/whathap/UBNRP/visionwebsite04/twotypes.html
- http://www.nlm.nih.gov/
- http://www.newton.dep.anl.gov/askasci/mole00/mole00087.htm
- http://www.hhmi.org/biointeractive/vlabs/cardiology/content/dtg/pedigree/pedigree.html
- http://www.ndsu.nodak.edu/instruct/mcclean/plsc431/mendel/mendel9.htm
- http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookgeninteract.html

Vocabulary

autosome Any chromosome other than a sex chromosome.

carrier A person who is heterozygous for a recessive allele of a trait.

codominance Occurs when both traits appear in a heterozygous individual.

incomplete dominance Occurs when the phenotype of the offspring is somewhere in between the phenotypes of both parents; a completely dominant allele does not occur.

Mendelian trait A trait that is controlled by a single gene that has two alleles.

multiple alleles When three or more alleles determine a trait, such as with the human ABO blood group.

probability The likelihood that a certain event will occur.

pedigree A chart which shows the inheritance of a trait over several generations.

polygenic traits Traits that are affected by more than one gene.

Punnett square A diagram that helps predict the probable inheritance of alleles in different crosses.

sex chromosome A chromosome that determines the sex of an organism.

sex-linked trait A trait whose allele is found on a sex chromosome.

testcross A cross used to determine an unknown genotype.

Points to Consider

The next chapter is *Molecular Genetics.*

- What do you think Molecular Genetics refers to?
- How can DNA contain all the genetic information?
- If DNA is in the nucleus, and proteins are made on ribosomes in the cytoplasm, how do you think this happens?

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Chapter 8

Molecular Genetics

8.1 Lesson 8.1: DNA and RNA

Lesson Objectives

- Discuss how the work of Griffith, Avery, Hershey, and Chase demonstrated that DNA is the genetic material.
- Define transformation and explain that transformation is the change in genotype and phenotype due to the assimilation of the external DNA by a cell.
- Discuss the findings of Chargaff. Describe the importance of the finding that in DNA, the amount of adenine and thymine were about the same and that the amount of guanine and cytosine were about the same. This finding lead to the base pairing rules.
- Explain Watson and Crick's double helix model of DNA.
- Describe how DNA is replicated.
- Explain the importance of the fact that during DNA replication, each strand serves as a template to make a complementary DNA strand.
- Describe the structure and function of RNA.
- Discuss the role of the three types of RNA: mRNA, rRNA, and tRNA.

Introduction

What tells the first cell of an organism what to do? How does that first cell know to become two cells, then four cells, and so on? Does this cell have instructions? What are those instructions and what do they really do? What happens when those instructions don't work properly? Are the "instructions" the genetic material? Though today it seems completely obvious that Deoxyribonucleic acid, or **DNA**, is the genetic material, this was not always known.

DNA and RNA

Practically everything a cell does, be it a liver cell, a skin cell, or a bone cell, it does because of proteins. It is your proteins that make a bone cell act like a bone cell, a liver cell act like a liver cell, or a skin cell act like a skin cell. In other words, it is the proteins that give an organism its traits. We know that it is your proteins that that make you tall or short, have light or dark skin, or have brown or blue eyes. But what tells those proteins how to act? It is the structure of the protein that determines what it does. And it is the order and type of **amino acids** that determine the structure of the protein. And that order and type of amino acids that make up the protein are determined by your DNA sequence.

The relatively large chromosomes that never leave the nucleus are made of DNA. And, as proteins are made on the ribosomes in the cytoplasm, how does the information encoded in the DNA get to the site of protein synthesis? That's where RNA comes into this three-player act.

DNA → RNA → Protein

That's known as the central dogma of molecular biology. It states that "DNA makes RNA makes protein." This process starts with DNA. And first DNA had to be identified as the genetic material.

The Hereditary Material

For almost 100 years, scientists have known plenty about proteins. They have known that proteins of all different shapes, sizes, and functions exist. For this reason, many scientists believed that proteins were the heredity material. It wasn't until 1928, when Frederick Griffith identified the process of transformation, that individuals started to question this concept. Griffith demonstrated that transformation occurs, but what was the material that caused the transforming process?

Griffith, Avery, Hershey and Chase

Griffith was studying *Streptococcus pneumoniae*, a bacterium that infects mammals. He used two strains, a virulent S (smooth) strain and a harmless R (rough) strain to demonstrate the transfer of genetic material. The S strain is surrounded by a polysaccharide capsule, which protects it from the host's immune system, resulting in the death of the host, while the R strain, which does not have the protective capsule, is defeated by the host's immune system. Hence, when mammalian cells are infected with the R strain bacteria, the host does not die (**Figure** 8.1).

Griffith infected mice with heat-killed S strain bacteria. As expected, the heat-killed bacteria, as they were dead, had no effect on the mice (Figure 1). But then he tried something different.

He mixed the remains of heat-killed S strain bacteria with live R strain bacteria and injected the mixture into mice. Remember, separately both of these bacteria are harmless to the mice. And yet the mice died (**Figure** 8.1). Why? These mice had both live R and live S strain bacteria in their blood. How? Griffith concluded that the R strain had changed, or transformed, into the lethal S strain. Something, such as the "instructions" from the remains of the S strain, had to move into the R strain in order to turn the harmless R strain into the lethal S strain. This material that was transferred between strains had to be the heredity material. But the transforming material had yet to be identified. **Transformation** is now known as the change in genotype and phenotype due to the assimilation of external DNA (heredity material) by a cell.

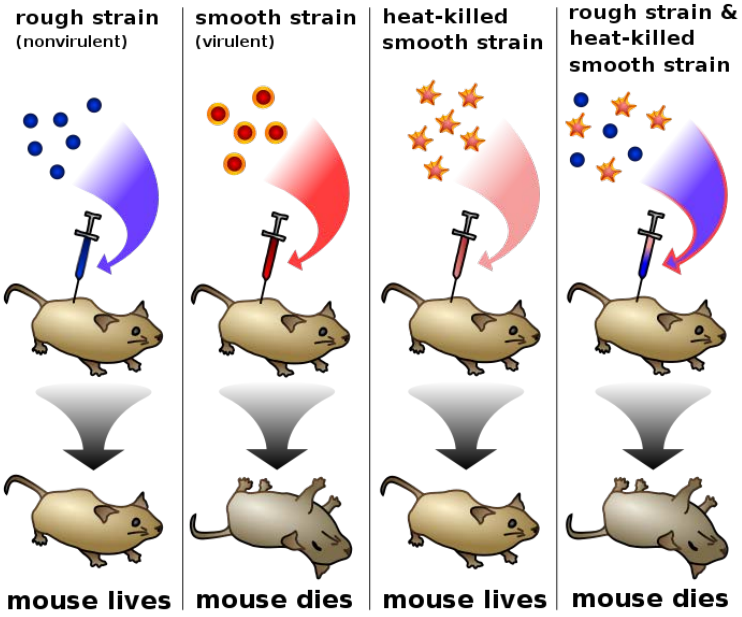

Figure 8.1: The transformation experiments of Griffith. The rough (R) strain has no effect on the mouse, whereas the smooth (S) strain is harmful to the mouse. Heat-killed S strain also has no effect on the mouse, but the mixture of heat-killed S strain and the R strain is harmful to the mouse.

Over the next decade, scientists, led by Oswald Avery, tried to identify the material involved in transformation. Avery, together with his colleagues Maclyn McCarty and Colin MacLeod, removed various organic compounds from bacteria and tested the remaining compounds for the ability to cause transformation. If the remaining material did not cause transformation, than that material could not be the heredity material. Avery treated S strain bacteria with protease enzymes, which remove proteins from cells, and then mixed the remainder with R strain bacteria. The R strain bacteria transformed, meaning that proteins did not carry the genes for causing the disease. Then the remnants of the S strain bacteria were treated with **deoxyribonuclease**, an enzyme which degrades DNA. After this treatment, the R strain

bacteria no longer transformed. This indicated that DNA was the heredity material. The year was 1944.

However, this finding was not widely accepted, partly because so little was known about DNA. It was still thought that proteins were better candidates to be the heredity material. The structure of DNA was still unknown, and many scientists were not convinced that genes from bacteria and more complex organisms could be similar.

In 1952, Alfred Hershey and Martha Chase put this skepticism to rest. They conclusively demonstrated that DNA is the genetic material. Hershey and Chase used the T2 **bacteriophage**, a virus that infects bacteria, to prove this point. A virus is essentially DNA (or RNA) surrounded by a protein coat (**Figure** 8.2). To reproduce, a virus must infect a cell and use that host cell's machinery to make more viruses. The T2 bacteriophage can quickly turn an *Escherichia coli (E. coli)* bacteria into a T2 producing system. But to do that, the genetic material from T2, which could only be protein or DNA, must be transferred to the bacteria. Which one was it?

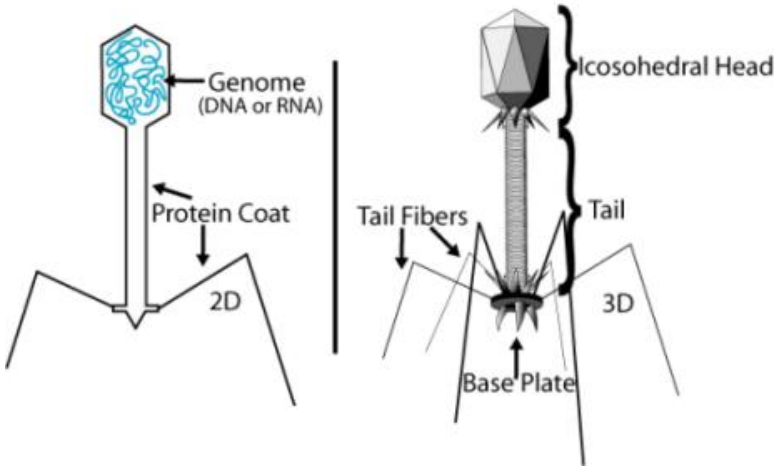

Figure 8.2: Structural overview of T2 phage. A 2-dimensional representation is on the left, and a 3-dimensional representation is on the right. The phage is essentially nucleic acid surrounded by a protein coat.

Hershey and Chase performed a series of classic experiments, taking advantage of the fact that T2 is essentially just DNA and protein. In the experiments, T2 phages with either radioactive ^{32}P-labeled DNA or radioactive ^{35}S-labeled protein were used to infect bacteria. Either the radioactive proteins or radioactive DNA would be transferred to the bacteria. Identifying which one is transferred would identify the genetic material. In both experiments, bacteria were separated from the phage coats by blending, followed by centrifugation. Only the radioactively labeled DNA was found inside the bacteria, whereas the radioactive proteins stayed in the solution (**Figure** 8.3). These experiments demonstrated that DNA is the genetic material and that protein does not transmit genetic information.

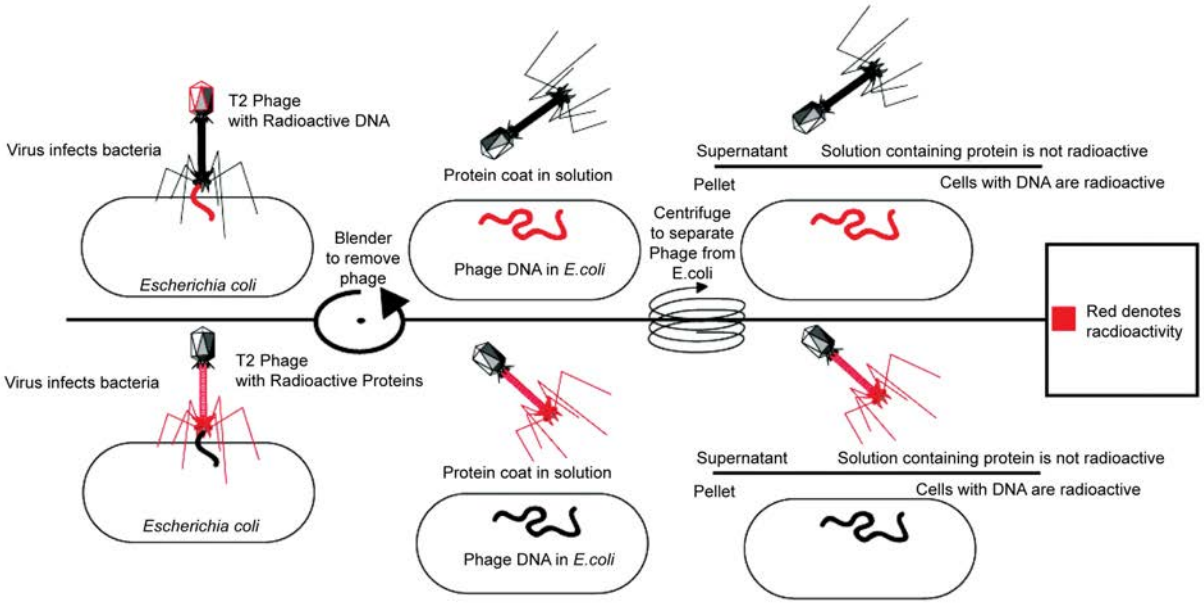

Figure 8.3: The Hershey and Chase experiment. T2 virus with either radioactive DNA (upper section) or radioactive protein (lower section) were used to infect bacteria. A blender was used to remove the phage from the bacteria followed by centrifugation. The radioactive DNA was found inside the bacteria (upper section), demonstrating that DNA is the genetic material.

Chargaff's Rules

It was known that DNA is composed of **nucleotides**, each of which contains a nitrogen-containing base, a five-carbon sugar (deoxyribose), and a phosphate group. In these nucleotides, there is one of the four possible bases: adenine (A), guanine (G), cytosine (C), or thymine (T) (**Figure** 8.4).

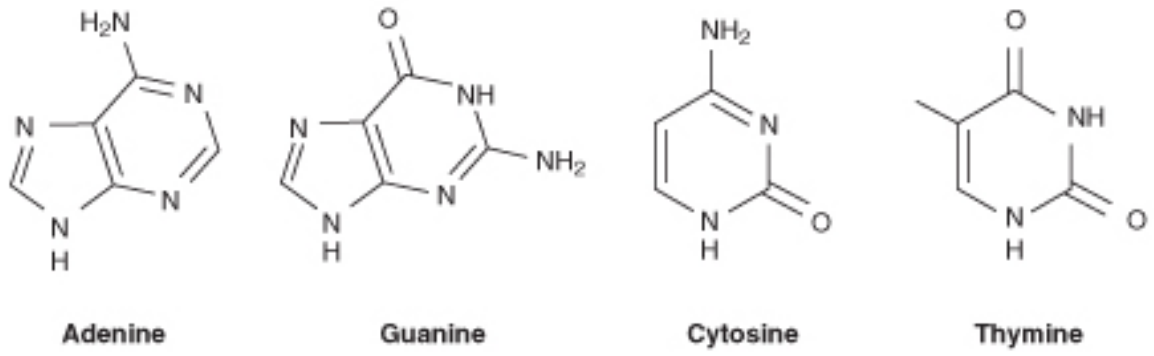

Figure 8.4: Chemical structure of the four nitrogenous bases in DNA.

Erwin Chargaff proposed two main rules that have been appropriately named Chargaff's rules. In 1947 he showed that the composition of DNA varied from one species to another. This molecular diversity added evidence that DNA could be the genetic material. Chargaff also determined that in DNA, the amount of one base always approximately equals the amount of a particular second base. For example, the number of guanines equals the number of cytosines, and the number of adenines equals the number of thymines. Human DNA is 30.9% A and 29.4% T, 19.9% G and 19.8% C. This finding, together with that of the DNA structure, led to the base-pairing rules of DNA.

The Double Helix

In the early 1950s, Rosalind Franklin started working on understanding the structure of DNA fibers. Franklin, together with Maurice Wilkins, used her expertise in x-ray diffraction photographic techniques to analyze the structure of DNA. In February 1953, Francis Crick and James D. Watson of the Cavendish Laboratory in Cambridge University had started to build a model of DNA. Watson and Crick indirectly obtained Franklin's DNA X-ray diffraction data demonstrating crucial information into the DNA structure. Francis Crick and James Watson (**Figure** 8.5) then published their double helical model of DNA in *Nature* on April 25th, 1953.

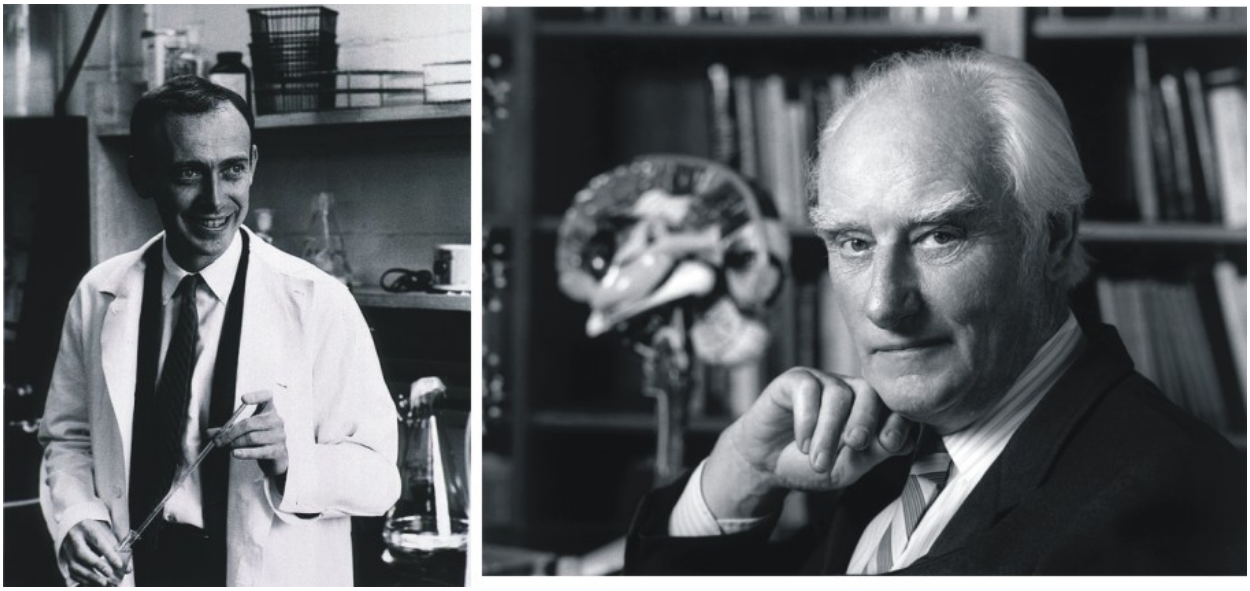

Figure 8.5: James Watson (left) and Francis Crick (right).

DNA has the shape of a **double helix**, just like a spiral staircase (**Figure** 8.6). There are two sides, called the **sugar-phosphate backbone**, because they are made from alternating phosphate groups and deoxyribose sugars. The "steps" of the double helix are made from the base pairs formed between the nitrogenous bases. The DNA double helix is held together by hydrogen bonds between the bases attached to the two strands.

The double helical nature of DNA, together with the findings of Chargaff, demonstrated the base-pairing nature of the bases. Adenine always pairs with thymine, and guanine always pairs with cytosine (**Figure** 8.7). Because of this complementary nature of DNA, the bases on one strand determine the bases on the other strand. These complementary base pairs explain why the amounts of guanine and cytosine are present in equal amounts, as are the amounts of adenine and thymine. Adenine and guanine are known as **purines**. These bases consist of two ring structures. Purines make up one of the two groups of nitrogenous bases. Thymine and cytosine are **pyrimidines**, which have just one ring structure. By having a purine always combine with a pyrimidine in the DNA double helix, the distance between the two sugar-phosphate backbones is constant, maintaining the uniform shape of the DNA molecule.

The two strands in the DNA backbone run in **anti-parallel** directions to each other. That is, one of the DNA strands is built in the 5' $\rightarrow$ 3' direction, while the complementary strand is built in the 3' $\rightarrow$ 5' direction. In the DNA backbone, the sugars are joined together by phosphate groups that form bonds between the third and fifth carbon atoms of adjacent sugars. In a double helix, the direction of the nucleotides in one strand is opposite to their direction in the other strand. 5' and 3' each mark one end of a strand. A strand running in the 5'$\rightarrow$ 3' direction that has adenine will pair with base thymine on the complementary

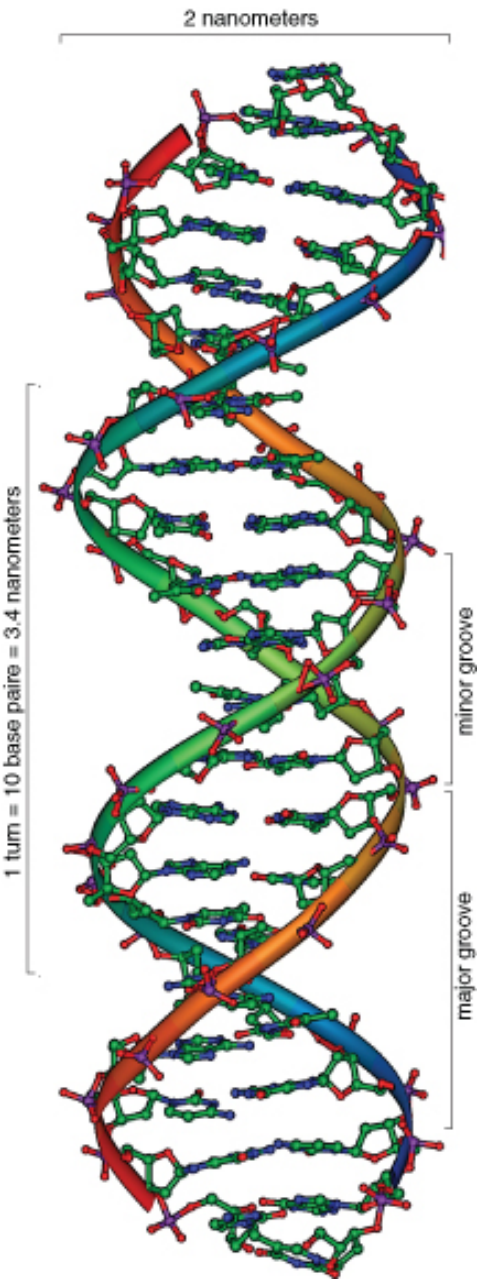

Figure 8.6: The DNA double helix. The two sides are the sugar-phosphate backbones, composed of alternating phosphate groups and deoxyribose sugars. The nitrogenous bases face the center of the double helix.

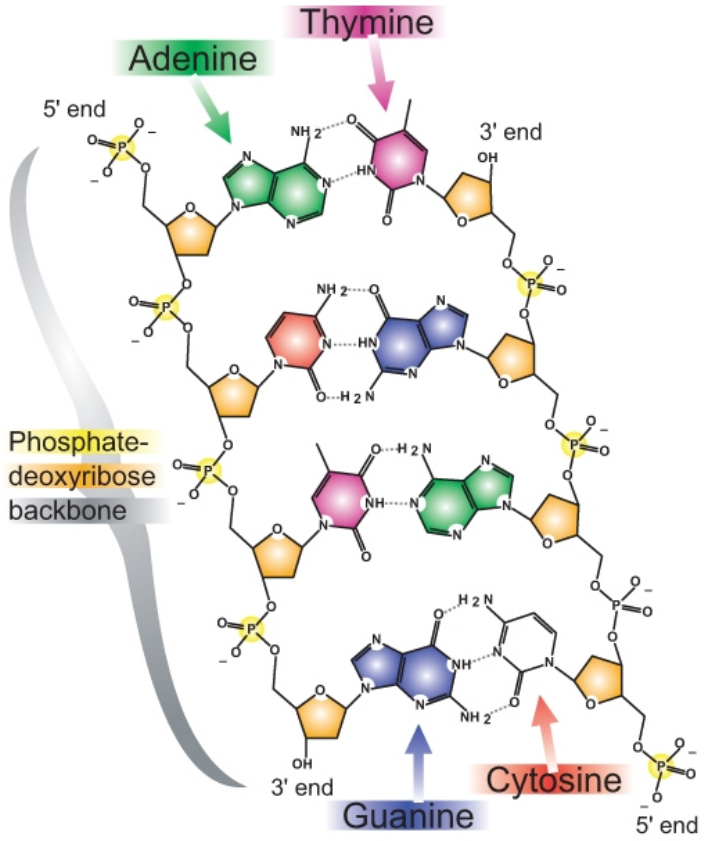

Figure 8.7: The base-pairing nature of DNA. Adenine always pairs with thymine, and they are held together with two hydrogen bonds. The guanine-cytosine base pair is held together with three hydrogen bonds. Note that one sugar-phosphate backbone is in the 5'→ 3' direction, with the other strand in the opposite 3'→ 5' orientation.

strand running in 3'→ 5' direction.

So it is this four letter code, made of just A, C, G, and T, that determines what the organism will become and what it will look like. How can these four bases carry so much information? This information results from the order of these four bases in the chromosomes. This sequence carries the unique genetic information for each species and each individual. Humans have about 3,000,000,000 bits of this information in each cell. A gorilla may also have close to that amount of information, but a slightly different sequence. For example, the sequence AGGTTTACCA will have different information than CAAGGGATTA. The closer the evolutionary relationship is between two species, the more similar their DNA sequences will be. For example, the DNA sequences between two species of reptiles will be more similar than between a reptile and an elm tree.

DNA sequences can be used for scientific, medical, and forensic purposes. DNA sequences can be used to establish evolutionary relationships between species, to determine a person's susceptibility to inherit or develop a certain disease, or to identify crime suspects or victims. Of course, DNA analysis can be used for other purposes as well. So why is DNA so useful for these purposes? It is useful because every cell in an organism has the same DNA sequence. For this to occur, each cell must have a mechanism to copy its entire DNA. How can so much information be exactly copied in such a small amount of time?

DNA Replication

DNA replication is the process in which a cell's entire DNA is copied, or replicated. This process occurs during the Synthesis (S) phase of the eukaryotic cell cycle. As each DNA strand has the same genetic information, both strands of the double helix can serve as templates for the reproduction of a new strand. The two resulting double helices are identical to the initial double helix. For an animation of DNA replication, see http://www.hhmi.org/biointeractive/media/DNAi_replication_vo1-sm.mov.

Helicase and Polymerase

DNA replication begins as an enzyme, **DNA helicase**, breaks the hydrogen bonds holding the two strands together and forms a replication fork. The resulting structure has two branching strands of DNA backbone with exposed bases. These exposed bases allow the DNA to be "read" by another enzyme, **DNA polymerase**, which then builds the complementary DNA strand. As DNA helicase continues to open the double helix, the replication fork grows.

5' → 3'

The two new strands of DNA are "built" in opposite directions, through either a **leading strand** or a **lagging strand**. The leading strand is the DNA strand that DNA polymerase constructs in the 5' → 3' direction. This strand of DNA is made in a continuous manner,

moving as the replication fork grows. The lagging strand is the DNA strand at the opposite side of the replication fork from the leading strand. It goes in the opposite direction, from 3' to 5'. DNA polymerase cannot build a strand in the 3' → 5' direction. Thus, this "lagging" strand is synthesized in short segments known as **Okazaki fragments**. On the lagging strand, an enzyme known as **primase** builds a short RNA primer. DNA polymerase is then able to use the free 3' OH group on the RNA primer to make DNA in the 5' → 3' direction. The RNA fragments are then degraded and new DNA nucleotides are added to fill the gaps where the RNA was present. Another enzyme, **DNA ligase**, is then able to attach (ligate) the DNA nucleotides together, completing the synthesis of the lagging strand (**Figure** 8.8).

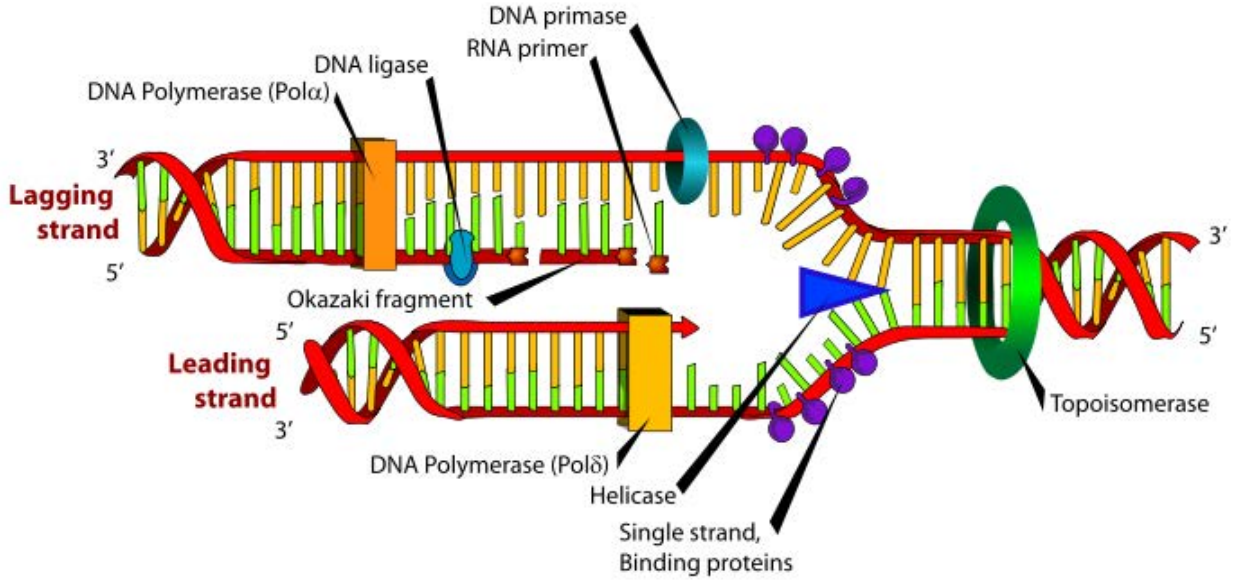

Figure 8.8: DNA replication. The two DNA strands are opened by helicase. The strands are held open by a single strand of binding proteins, preventing premature reannealing. Topoisomerase solves the problem caused by tension generated by winding/unwinding of DNA. This enzyme wraps around DNA and makes a cut permitting the helix to spin and relax. Once DNA is relaxed, topoisomerase reconnects broken strands. DNA primase synthesizes a short RNA primer which initiates the Okazaki fragment. Okazaki fragments are attached by DNA ligase.

Many replication forks develop along a chromosome. This process continues until the replication forks meet, and the all of the DNA in a chromosome has been copied. Each new strand that has formed is complementary to the strand used as the template. Each resulting DNA molecule is identical to the original DNA molecule. During prophase of mitosis or prophase I of meiosis, these molecules of DNA condense into a chromosome made of two identical chromatids. This process ensures that cells that result from cell division have identical sets of genetic material, and that the DNA is an exact copy of the parent cell's DNA.

RNA

DNA → RNA → Protein

"DNA makes RNA makes protein." So what exactly is RNA? Ribonucleic acid, or **RNA**, is the other important nucleic acid in the three player act. When we say that "DNA makes RNA makes protein," what do we mean? We mean that the information in DNA is somehow transferred into RNA, and that the information in RNA is then used to make the protein.

To understand this, it helps to first understand RNA. If you remember from the chapter titled *Cell Division and Reproduction*, a **gene** is a segment of DNA that contains the information necessary to encode an RNA molecule or a protein. Keep in mind that even though you have many thousands of genes, not all are used in every cell type. In fact, probably only a few thousand are used in a particular type of cell, with different cell types using different genes. However, while these genes are embedded in the large chromosomes that never leave the nucleus, the RNA is relatively small and is able to carry information out of the nucleus.

RNA Structure

RNA structure differs from DNA in three specific ways. Both are nucleic acids and made out of nucleotides; however, RNA is single stranded while DNA is double stranded. RNA contains the 5-carbon sugar ribose, whereas in DNA, the sugar is deoxyribose. Though both RNA and DNA contain the nitrogenous bases adenine, guanine and cytosine, RNA contains the nitrogenous base uracil instead of thymine. Uracil pairs with adenine in RNA, just as thymine pairs with adenine in DNA. A comparison of RNA and DNA is shown in **Table** 8.1 and **Figure** 8.9.

Table 8.1: **A Comparison of RNA and DNA**

	RNA	DNA
	single stranded	double stranded
Specific Base	contains uracil	contains thymine
Sugar	ribose	deoxyribose
Size	relatively small	big (chromosomes)
Location	moves to cytoplasm	stays in nucleus
Types	3 types: mRNA, tRNA, rRNA	generally 1 type

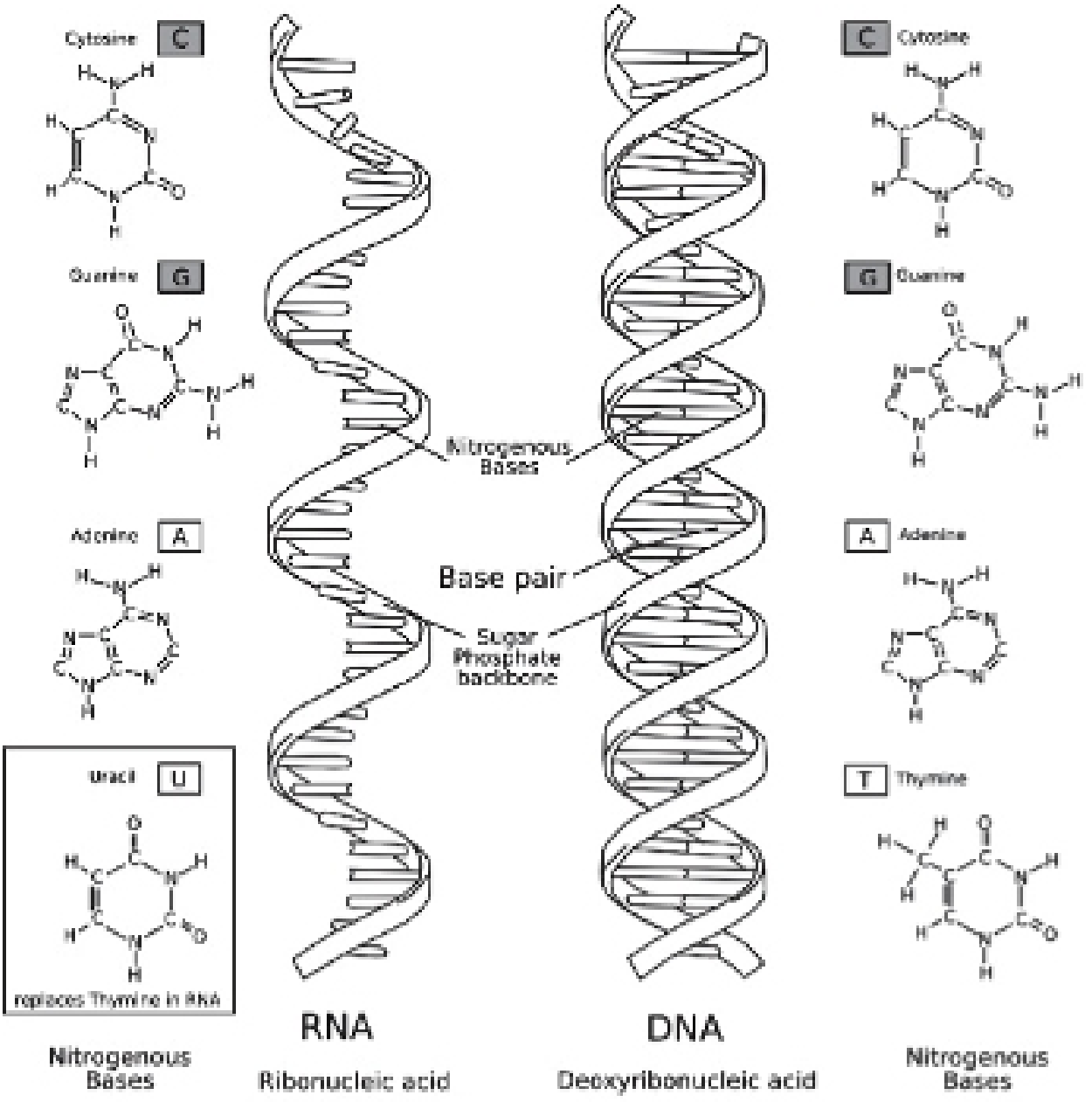

Figure 8.9: A comparison of RNA and DNA. RNA is single stranded and contains the base uracil, which replaces thymine.

Three Types of RNAs

So what does RNA do? There are three types of RNA: messenger RNA (mRNA), transfer RNA (tRNA), and ribisomal RNA (rRNA). All three of these nucleic acids work together to produce a protein. The **mRNA** takes the instructions from the nucleus to the cytoplasm, where the ribosomes are located. **Ribosomes** are where the proteins are made. The ribosomes themselves are made out of **rRNA** and other proteins. The mRNA binds to the ribosome, bringing the instructions to order the amino acids to the site of protein synthesis. Finally, the **tRNA** brings the correct amino acid to the site of protein synthesis (**Figure** 8.10 and **Figure** 8.11). In mRNA, the four nucleotides (A, C, G, and U) are arranged into **codons** of three bases each. Each codon encodes for a specific amino acid, except for the stop codons, which terminate protein synthesis. tRNA, which has a specific "3-leaf clover structure," contains a three base region called the **anticodon**, which can base pair to the corresponding three-base codon region on mRNA. More will be discussed on these processes during the lesson on translation that follows.

Remember, proteins are made out of amino acids, so how does the information get converted from the language of nucleotides to the language of amino acids? The process is called **translation**.

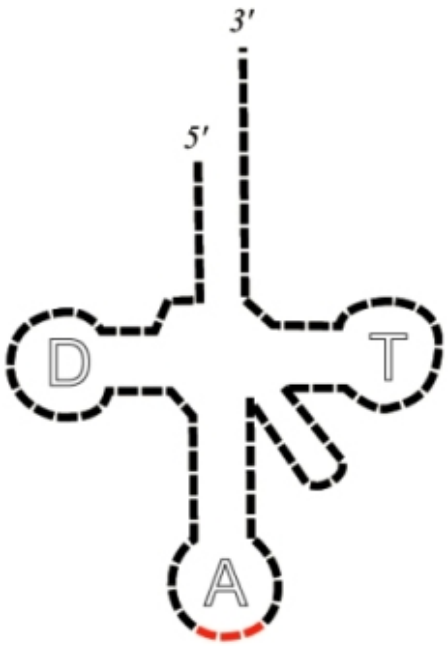

Figure 8.10: 2-Dimensional tRNA structure depicting the 3-leaf clover structure. The D arm (D) is one stem ending in a loop. The anticodon arm (A) is a second stem whose loop contains the anticodon on the bottom of the tRNA. The T arm (T) is the third stem opposite the D arm.

Figure 8.11: 3-Dimensional representation of a tRNA. Coloring: CCA tail in orange, Acceptor stem in purple, D arm in red, Anticodon arm in blue with Anticodon in black, and T arm in green. The acceptor stem is made by the base pairing of the 5'-terminal nucleotide with the 3'-terminal nucleotide. The CCA tail is a CCA sequence at the 3' end of the tRNA molecule, used to attach the amino acid. This sequence is important for the recognition of tRNA by enzymes critical in translation.

Small interfering RNA (siRNA), microRNA (miRNA) and small nuclear RNA (snRNA): siRNA and miRNA are revolutionizing molecular biology, developmental biology, and even medicine. The 2006 Nobel prize in Physiology and Medicine was awarded to Dr. Andrew Fire and Dr. Craig Mello for their discovery of siRNA, which is a type of double-stranded RNA that inhibits gene expression at the mRNA level. Specifically, siRNA acts on homologous processed mRNA by targeting it for degradation. siRNA is responsible for RNA interference (RNAi). RNAi has a natural role in that it is used by plants in defense against plant viral RNAs. miRNAs are also involved in the regulation of gene expression. They are transcribed but not translated into proteins. snRNAs are found within the nucleus of eukaryotic cells. They are involved in a variety of important processes such as RNA splicing (removal of introns), and regulation of **transcription** factors (discussed in Lesson 8.2: Protein Synthesis).

Lesson Summary

- Griffith demonstrated the process of transformation, which is the change in genotype and phenotype due to the assimilation of the external DNA by a cell.
- Avery and colleagues demonstrated that DNA was the transforming material.
- The Hershey and Chase experiments conclusively demonstrated that DNA is the genetic material.
- Watson and Crick demonstrated the double helix model of DNA.
- The Base paring rules state that A always pairs with T and G always pairs with C.
- DNA replication is the process by which a cell's entire DNA is copied, or replicated.
- During DNA replication, the two new strands of DNA are "built" in opposite directions, starting at replication forks.
- RNA is a single-stranded nucleic acid.
- RNA contains the nitrogenous base uracil.
- There are three types of RNA: mRNA, tRNA, and rRNA.
- mRNA is the intermediary between the nucleus, where the DNA lives, and the cytoplasm, where proteins are made.

Review Questions

1. Discuss how DNA was identified as the genetic material.
2. Define transformation.
3. In DNA, why does the amount of adenine approximately equal the amount of thymine?
4. What are the base pairing rules?
5. Explain Watson and Crick's double helix model of DNA.
6. How is DNA replicated?
7. Discuss the importance of mRNA.
8. Explain the main differences between mRNA, rRNA,and tRNA.

Further Reading / Supplemental Links

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- http://www.dnalc.org/home_alternate.html
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- A Science Odyssey:
- http://www.pbs.org/wgbh/aso/tryit/dna/
- National Human Genome Research Institute:
- http://www.genome.gov
- The RNA Modification Database:
- http://library.med.utah.edu/RNAmods/
- The RNA World:
- http://nobelprize.org/nobel_prizes/chemistry/articles/altman/index.html
- http://en.wikipedia.org

Vocabulary

amino acid The monomers that combine to form a polypeptide (protein).

anticodon A 3 base sequence on the tRNA that base pairs with the codon on the mRNA.

anti-parallel Describes the orientation of the two DNA strands; one of the DNA strands is built in the 5' → 3' direction, while the complementary strand is built in the 3' → 5' direction.

bacteriophage A virus that infects bacteria.

codon A sequence of three nucleotides within mRNA; encodes for a specific amino acid or termination (stop) sequence.

deoxyribonuclease An enzyme which degrades DNA.

DNA Deoxyribonucleic acid, the genetic (heredity) material.

DNA polymerase The enzyme that builds a new DNA strand during DNA replication.

DNA helicase The enzyme that breaks the hydrogen bonds holding the two DNA strands together during DNA replication.

DNA ligase An enzyme that joins broken nucleotides together by catalyzing the formation of a bond between the phosphate group and deoxyribose sugar of adjacent nucleotides in the DNA backbone.

DNA replication The process in which a cell's entire DNA is copied.

double helix The shape of DNA, resembling a spiral staircase.

gene A segment of DNA that contains the information necessary to encode an RNA molecule or a protein.

lagging strand The DNA strand at the opposite side of the replication fork from the leading strand.

leading strand The DNA strand that DNA polymerase constructs in the 5' $\rightarrow$ 3' direction.

mRNA Messenger RNA; serves as a nucleic acid intermediate between the nucleus and the ribosomes.

nucleotide Monomer of nucleic acids, composed of a nitrogen-containing base, a five-carbon sugar, and a phosphate group.

Okazaki fragments Short fragments of DNA that comprise the lagging strand.

primase An enzyme that builds a short RNA primer on the lagging strand during DNA replication.

purines Nitrogenous bases consisting of two ring structures; adenine and guanine.

pyrimidines Nitrogenous bases consisting of one ring structure; thymine and cytosine.

ribosome Non-membrane bound organelle; site of protein synthesis.

RNA Ribonucleic acid; single-stranded nucleic acid.

rRNA Ribosomal RNA; together with proteins, forms ribosomes.

sugar-phosphate backbone The sides of the DNA double helix; composed of alternating phosphate groups and deoxyribose sugars.

transcription The process of making an mRNA from the information in the DNA sequence.

translation The process of making a protein from the information in a mRNA sequence.

transformation The change in genotype and phenotype due to the assimilation of external DNA (heredity material) by a cell.

tRNA Transfer RNA; brings amino acids to the ribosome.

Points to Consider

- "DNA → RNA" Can you think of a method in which the information in DNA is transferred to an RNA molecule?
- Can you hypothesize on how the As, Cs, Gs and Us of RNA can code for the 20 amino acids of proteins?
- Can you develop a model in which the three types of RNAs interact to make a protein?

8.2 Lesson 8.2: Protein Synthesis

Lesson Objectives

- Discuss the meaning of DNA → RNA → Protein.
- Describe how transcription makes RNA from a DNA template.
- Explain the various types of modification mRNA undergoes before translation.
- Discuss mRNA splicing and define introns and exons.
- Explain how the Genetic Code is a three letter code, and describe its role in translating nucleotides into amino acids.
- Explain that a reading frame is the group of three bases in which the mRNA is read, and describe how interrupting the reading frame may have severe consequences on the protein.
- Discuss what is meant by the universal genetic code.

- Describe translation. Explain that translation is the process of ordering the amino acids into a polypeptide; translation involves changing the language of nucleotides into the language of amino acids.
- Illustrate the process of translation, describing how mRNA, rRNA, and tRNA all work together to complete the process.
- Discuss what happens to the polypeptide after translation.

DNA → RNA → Protein

The central dogma of molecular biology describes the fundamental process that makes us all different. We all have different proteins. That is, though they may be the same types of proteins, such as we have the protein collagen found in bones, many of our proteins are slightly different and thus work slightly differently. If all our proteins acted the same way, we would all be exactly the same. But because we all have different DNA sequences, and DNA contains genes, and **genes** contain the information to encode an RNA molecule or a protein, we are all different.

So how does "DNA makes RNA makes protein" actually happen? The two processes necessary to make a protein from the information in DNA are transcription and translation. Transcription, which happens in the nucleus, uses the DNA sequence to make an RNA molecule. The RNA then leaves the nucleus and goes to the cytoplasm where translation occurs on a ribosome and produces a protein.

Transcription

Transcription is "DNA → RNA." In other words, transcription is the transfer of the genetic "instructions" from DNA to RNA. During transcription, a complementary copy of RNA is made. Whereas in DNA replication both strands of the DNA double helix are used as templates, in transcription only one strand is needed. RNA polymerase enzymatically "reads" a template strand of DNA, known as the coding strand, to synthesize the complementary RNA strand. Transcription is divided into 3 stages, appropriately named initiation, elongation and termination. For an animation of transcription, see http://www.hhmi.org/biointeractive/media/DNAi_transcription_vo1-sm.mov.

Initiation

Transcription begins with the binding of RNA polymerase to the promoter of a gene. An eukaryotic promoter usually includes specific sequences that are recognized by transcription factors, which are proteins that aid in the binding of RNA polymerase to the correct place on the DNA. The transcription initiation complex formed by the promoter, transcription factors, and RNA polymerase signals the start, or **initiation**, of transcription. The DNA

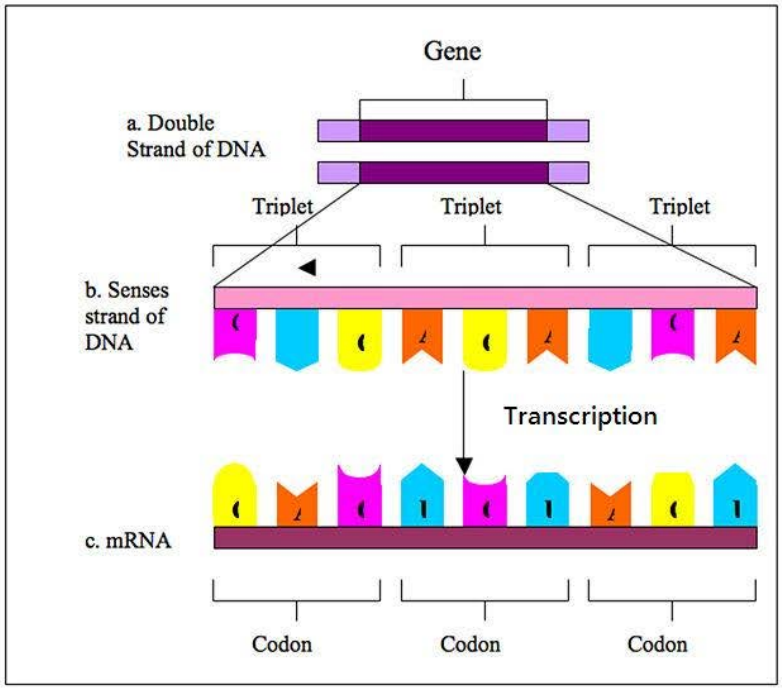

Figure 8.12: Each gene (a) contains triplets of bases (b) that are transcribed into RNA (c). Every triplet, or codon, encodes for a unique amino acid.

unwinds and produces a small open complex, which allows **RNA polymerase** to "read" the DNA template and begin the synthesis of RNA.

Elongation

Transcription **elongation** involves the further addition of RNA nucleotides and the change of the open complex to a transcriptional complex. As the RNA transcript is assembled, DNA in front of RNA polymerase unwinds and transcription continues. As transcription progresses, RNA nucleotides are added to the 3' end of the growing RNA transcript. The transcriptional complex has a short DNA-RNA hybrid, an 8 base-pair stretch in which the newly made RNA is temporarily hydrogen bonded to the DNA template strand. Unlike DNA replication, mRNA transcription can involve multiple RNA polymerases, allowing numerous mRNAs to be produced from a single copy of the gene. This step also involves a proofreading mechanism that can replace an incorrectly added RNA nucleotide.

Termination

The termination of transcription in prokaryotes and eukaryotes is very different. Though both involve the detachment of the RNA from the DNA template, how this occurs is surprisingly distinct. Bacteria use two different strategies for transcription termination, Rho-dependent and Rho-independent termination. In **Rho-dependent termination**, a protein factor called "Rho" destabilizes the RNA-DNA hybrid, releasing the newly synthesized mRNA from the elongation complex. In Rho-independent termination, RNA transcription stops when the newly synthesized RNA molecule forms a hairpin loop followed by a run of uracils. This structure is the signal for the detachment of the RNA from the DNA. The DNA is now ready for translation.

The **termination** of transcription in eukaryotes is less well understood. The RNA polymerase transcribes a polyadenylation signal. Polyadenylation is the addition of a string of A's to the mRNA's 3' end and will be discussed in the next section. However, soon after the transcription of this signal, proteins cut the RNA transcript free from the polymerase and the polymerase eventually falls off the DNA. This process produces a pre-mRNA, an mRNA that is not quite ready to be translated.

Eukaryotic mRNA Processing

Newly transcribed eukaryotic mRNA is not ready for translation. This mRNA requires extensive processing, and so is known as pre-mRNA. The modification processes include splicing, the addition of a 5' cap, editing, and polyadenylation. Once these process have occurred, the mature mRNA can be exported through the nuclear pore.

Splicing

Humans have approximately 22,000 genes, yet make many more proteins. How? A process called **alternative splicing** allows one mRNA to produce many polypeptides. To understand this concept, the structure of the pre-mRNA must be discussed.

Eukaryotic pre-mRNA contains introns and exons. An **exon** is the region of a gene that contains the code for producing a protein. Most genes contain many exons, with each exon containing the information for a specific portion of a complete protein. In many species, a gene's exons are separated by long regions of DNA that have no identified function. These long regions are introns, and must be removed prior to translation. **Splicing** is the process by which introns are removed (**Figure** 8.13). Sometimes a process called alternative splicing allows **pre-mRNA** messages to be spliced in several different configurations, allowing a single gene to encode multiple proteins. Splicing is usually performed by an RNA-protein complex called the spliceosome, but some RNA molecules have their own catalytic activity and are capable of acting like enzymes to catalyze their own splicing. For an animation of RNA splicing, see http://vcell.ndsu.edu/animations/mrnasplicing/first.htm.

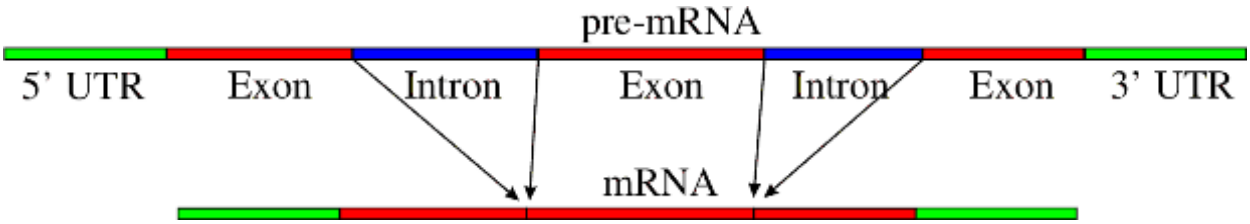

Figure 8.13: Splicing, the process by which introns (blue) are removed from pre-mRNA. Exons (red) contain the information used to produce the polypeptide. There are untranslated regions (UTR) at both the beginning and end of the pre-mRNA.

5' cap Addition

How does the mRNA know it is time to leave the nucleus? Once the mRNA leaves the nucleus, how does it find a ribosome? A signal on the front, 5'-end of the mRNA helps with both jobs. This signal is the 5' cap. The 5' cap is a modified guanine nucleotide added to the 5'-end of the pre-mRNA. This 5' cap is crucial for recognition and proper attachment of the mRNA to the ribosome, as well as protection from exonucleases, enzymes that degrade nucleic acids.

Editing

In certain instances, the nucleotide sequence of an mRNA will be changed to allow the mRNA to produce multiple proteins. This process is called **editing**. The classic example is editing

of the apolipoprotein B (APOB) mRNA in humans. The APOB protein occurs in the plasma in two main forms, APOB48 and APOB100. The first is synthesized exclusively by the small intestine, the second by the liver. Both proteins are coded for by the same gene, which is transcribed into a single pre-mRNA. Editing creates a premature (early) stop codon, which upon translation produces a smaller protein. As a result of the RNA editing, APOB48 and APOB100 share a common N-terminal sequence, but APOB48 lacks APOB100's C-terminal region.

Polyadenylation

In eukaryotic cells, the transcription of the polyadenylation signals indicates the termination of the process. The mRNA transcript is then cut off of the RNA polymerase and freed from the DNA. The cleavage site is characterized by the presence of the sequence AAUAAA near the end of the transcribed message. Polyadenylation then occurs. **Polyadenylation** is the addition of a poly(A) tail to the 3'-end of the mRNA. The poly(A) tail may consist of as many as 80 to 250 adenosine residues. The poly(A) tail protects the mRNA from degradation by exonucleases. Poladenylation is also important for transcription termination, export of the mRNA from the nucleus, and translation. For an animation on RNA polyadenylation, see http://vcell.ndsu.edu/animations/mrnaprocessing/first.htm.

The Genetic Code

So how exactly is the language of nucleotides used to code for the language of amino acids? How can a code of only As, Cs, Gs, and Us carry information for 20 different amino acids? The **genetic code** is the code in which the language of nucleotides is used to create the language of amino acids.

Cracking the Code

A code of at least three letters has to be the answer. A one letter code would only be able to code for four amino acids. A two letter code could only code for 16 amino acids. With a three letter code, there are 64 possibilities. As there are 20 amino acids, the answer must be a code of at least three letters.

In 1961, Francis Crick and Sydney Brenner demonstrated the presence of codons, that is, three bases of RNA that code for one amino acid (**Figure** 8.14). Also in 1961, Marshall Nirenberg and Heinrich Matthaei at the National Institutes of Health (NIH) demonstrated that a poly(U) RNA sequence was translated into a polypeptide consisting of only the amino acid phenylalanine. This proved that the codon UUU coded for the amino acid phenylalanine. Extending this work, Nirenberg and his coworkers were able to determine the nucleotide makeup of 54 of the 64 codons. Others determined the remainder of the genetic code (**Figure**

8.15).

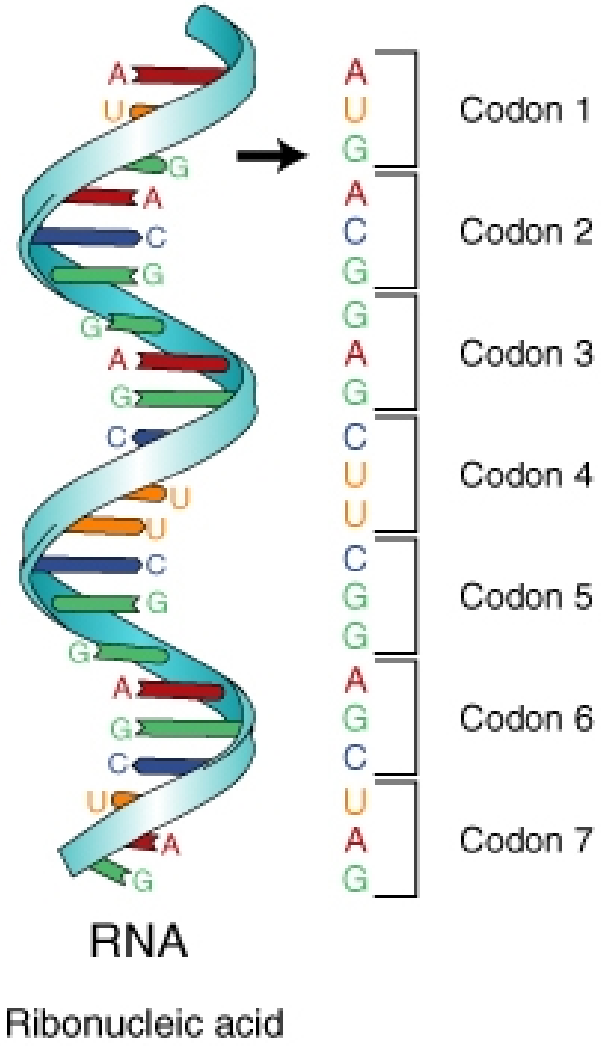

Figure 8.14: The mRNA is divided into three-base segments called codons. A codon is the segment of nucleotides that codes for an amino acid, or for a start or stop signal. There are 64 codons.

Start and Stop Codons

The codon AUG codes for the amino acid methionine. This codon is also the start codon which begins every translation of every amino acid chain. The translational machinery "reads" the mRNA codon by codon until it reaches a stop, or termination, codon. Stop

1st base		2nd base U	2nd base C	2nd base A	2nd base G
	U	UUU (Phe/F) Phenylalanine	UCU (Ser/S) Serine	UAU (Tyr/Y) Tyrosine	UGU (Cys/C) Cysteine
		UUC (Phe/F) Phenylalanine	UCC (Ser/S) Serine	UAC (Tyr/Y) Tyrosine	UGC (Cys/C) Cysteine
		UUA (Leu/L) Leucine	UCA (Ser/S) Serine	UAA Ochre (*Stop*)	UGA Opal (*Stop*)
		UUG (Leu/L) Leucine	UCG (Ser/S) Serine	UAG Amber (*Stop*)	UGG (Trp/W) Tryptophan
	C	CUU (Leu/L) Leucine	CCU (Pro/P) Proline	CAU (His/H) Histidine	CGU (Arg/R) Arginine
		CUC (Leu/L) Leucine	CCC (Pro/P) Proline	CAC (His/H) Histidine	CGC (Arg/R) Arginine
		CUA (Leu/L) Leucine	CCA (Pro/P) Proline	CAA (Gln/Q) Glutamine	CGA (Arg/R) Arginine
		CUG (Leu/L) Leucine	CCG (Pro/P) Proline	CAG (Gln/Q) Glutamine	CGG (Arg/R) Arginine
	A	AUU (Ile/I) Isoleucine	ACU (Thr/T) Threonine	AAU (Asn/N) Asparagine	AGU (Ser/S) Serine
		AUC (Ile/I) Isoleucine	ACC (Thr/T) Threonine	AAC (Asn/N) Asparagine	AGC (Ser/S) Serine
		AUA (Ile/I) Isoleucine	ACA (Thr/T) Threonine	AAA (Lys/K) Lysine	AGA (Arg/R) Arginine
		AUG[A] (Met/M) Methionine	ACG (Thr/T) Threonine	AAG (Lys/K) Lysine	AGG (Arg/R) Arginine
	G	GUU (Val/V) Valine	GCU (Ala/A) Alanine	GAU (Asp/D) Aspartic acid	GGU (Gly/G) Glycine
		GUC (Val/V) Valine	GCC (Ala/A) Alanine	GAC (Asp/D) Aspartic acid	GGC (Gly/G) Glycine
		GUA (Val/V) Valine	GCA (Ala/A) Alanine	GAA (Glu/E) Glutamic acid	GGA (Gly/G) Glycine
		GUG (Val/V) Valine	GCG (Ala/A) Alanine	GAG (Glu/E) Glutamic acid	GGG (Gly/G) Glycine

nonpolar polar basic acidic (stop codon)

Figure 8.15: The Genetic Code. The Genetic Code: Codons are in the mRNA sequence. The three letter and one letter code for the amino acids are shown. To read the code, find the first base on the left, the second base at the top, and the third base in the center of the table. For example, the codon GGG codes for the amino acid glycine (as does GGC, GGA, and GGU), CCG codes for Proline, UUA codes for Leucine, and AAG codes for Lysine. There are 64 codons that code for 20 amino acids and three stop codons, so an amino acid may have more than one corresponding codon.

codons are not associated with a tRNA or amino acid. Three are three stop codons: UAG, UGA, UAA.

The Reading Frame

The **reading frame** is the frame of three bases in which the mRNA is read or translated. Every sequence can be read in three reading frames, each of which will produce a different amino acid sequence. For example, in the sequence GCAUGGGGGUCUAG, the reading frame can begin with either the first G, the first C, or the first A. As stated above, **translation** starts with the start codon which consists of the three bases AUG. Each subsequent codon is translated until an in-frame stop codon is reached. In the example above, the polypeptide sequence would be: methionine – glycine – valine – stop.

Mutations that disrupt the reading frame by insertions or deletions of a non-multiple of 3 nucleotide bases are known as **frameshift mutations**. Take the example:

THE BIG FAT CAT ATE THE RED RAT

A deletion mutation that disrupts the reading frame, results in a message that does not make any sense. If the 'B' is deleted:

THE IGF ATC ATA TET HER EDR AT

Once the reading frame is disrupted, the mRNA may not be translated properly. These mutations may impair the function of the resulting protein, if the protein is even formed. Many frameshift mutations result in a premature stop codon, in other words, a stop codon that come earlier than normal during translation. This would result in a smaller protein, most likely without normal function.

Degeneracy of the Universal Genetic Code

When there are 64 codon combinations for 20 amino acids (and stop codons), there is going to be some overlap. Within the genetic code there is redundancy but no ambiguity. For example, the codons GGG, GGA, GGC, and GGU all encode the amino acid glycine, but none encode another amino acid. Degenerate codons often differ in the third position.

The genetic code is said to be universal. That is, the same code is utilized by the simplest prokaryotic organism and by humans. This universality is a tremendous benefit to mankind. If a human gene is placed in a bacteria, it looks just like a piece of DNA to the bacteria. The human As, Cs, Gs, and Ts look just like the bacteria's As, Cs, Gs, and Ts. So, the bacterial proteins will transcribe and translate this DNA, making a human protein.

But how exactly are these proteins made? We have been referring to mRNA's, tRNA's, ribosomes, codons and the genetic code throughout this chapter. How do they all come together to make a protein? The process is called translation.

Translation

Translation is "RNA → protein." In other words, translation is the transfer of the instructions in RNA to a protein made of amino acids. Translation uses the products of transcription, mRNA, tRNA, and rRNA, and converts the mRNA sequence into a polypeptide according to the genetic code. The mRNA moves to the cytoplasm and interacts with a **ribosome**, which serves as the site of translation. Translation proceeds in three phases: initiation, elongation and termination.

To understand translation, first we need to understand the ribosome. Ribosomes are composed of two subunits, a small subunit and a larger subunit. Prokaryotic subunits are named the 30S and 50S subunits; eukaryotic subunits are named the 40S and 60S subunits. During translation the tRNA molecules are literally "inside" the ribosomal subunits, as they sit on the mRNA strand. When tRNAs come to the ribosome, adjacent amino acids are brought together, allowing the ribosome to catalyze the formation of the peptide bond between amino acids. The ribosome has three tRNA binding sites: the A site, the P site, and the E site (**Figure** 8.16). The **A site** binds a tRNA with an attached amino acid. The P site contains the tRNA with the growing polypeptide chain attached, and the **E site** contains the tRNA that no longer has an attached amino acid. This tRNA is preparing to exit the ribosome. A single mRNA can be translated simultaneously by multiple ribosomes. For an animation of translation, see http://www.hhmi.org/biointeractive/media/DNAi_translation_vo1-sm.mov.

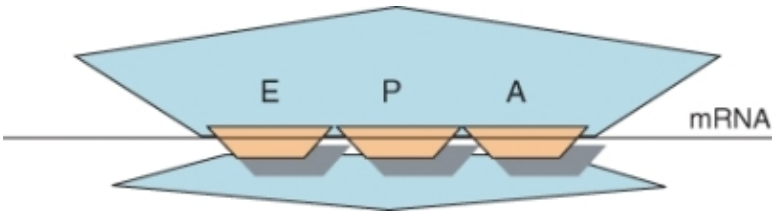

Figure 8.16: This cartoon depicts the relative location of the E, P, and A sites within the ribosome. The A site binds a tRNA bound to an amino acid, the binds a tRNA bound to the polypeptide being synthesized, and the E site binds a tRNA without an attached amino acid before the tRNA exits the ribosome.

Initiation in Prokaryotes

The initiation of translation in prokaryotes involves the assembly of the ribosome and addition of the first amino acid, methionine. The 30S ribosomal subunit attaches to the mRNA. Next, the specific methionine tRNA is brought into the P. The anticodon of this tRNA will bind to the AUG codon on the mRNA. This is the only time a tRNA will be brought into the P site; all successive tRNA's will be brought to the A site as translation continues. The 50S ribosomal subunit then binds to the 30S subunit, completing the ribosome.

Initiation in Eukaryotes

The initiation of protein translation in eukaryotes is similar to that of prokaryotes with some minor modifications. The 5' cap and 3' poly(A) tail are involved in the recruitment of the ribosome. In eukaryotes the ribosome scans along the mRNA for the first methionine codon. Translation may begin at all AUG codons, however only an in-frame AUG will produce a functional polypeptide. For an animation of translation, see http://vcell.ndsu.edu/animations/translation/first.htm.

Elongation

Elongation is fairly similar between prokaryotes and eukaryotes. As translation begins, the start tRNA is sitting on the AUG codon in the P site of the ribosome, so the next codon available to accept a tRNA is at the A site. Elongation proceeds after initiation with the binding of an tRNA to the A site. The next tRNA binds to the codon, bringing the appropriate amino acid to the ribosome, and a peptide bond joins between the start methionine and the next amino acid. The entire ribosome complex moves along the mRNA, sending the first tRNA into the E site and the tRNA with the growing polypeptide into the P site. The A site is now empty and ready to accept another tRNA. The first tRNA now leaves the ribosome. The A site accepts a tRNA with an attached amino acid, a peptide bond forms between the two adjacent amino acids, and the process continues.

Termination

Termination of translation occurs when the ribosome comes to one of the three stop codons, for which there is no tRNA. At this point, a protein called a release factor binds to the A site. The release factor causes the addition of a water molecule to the polypeptide chain, resulting in the release of the completed chain from the tRNA and ribosome. The ribosome, release factor, and tRNAs then dissociate and translation is complete. The process of translation is summarized in **Figure** 8.17.

Post-Translational Modification and Protein Folding

The events following protein synthesis often include post-translational modification of the peptide chain and folding of the protein into its functional conformation. During and after synthesis, polypeptide chains often fold into secondary and then tertiary structures. These levels of organization were discussed in the chapter titled *Chemical Basis of Life*. Briefly, the primary structure of the protein is determined by the gene. The secondary and tertiary structures are determined by interactions between the amino acids within the protein (**Figure** 8.18).

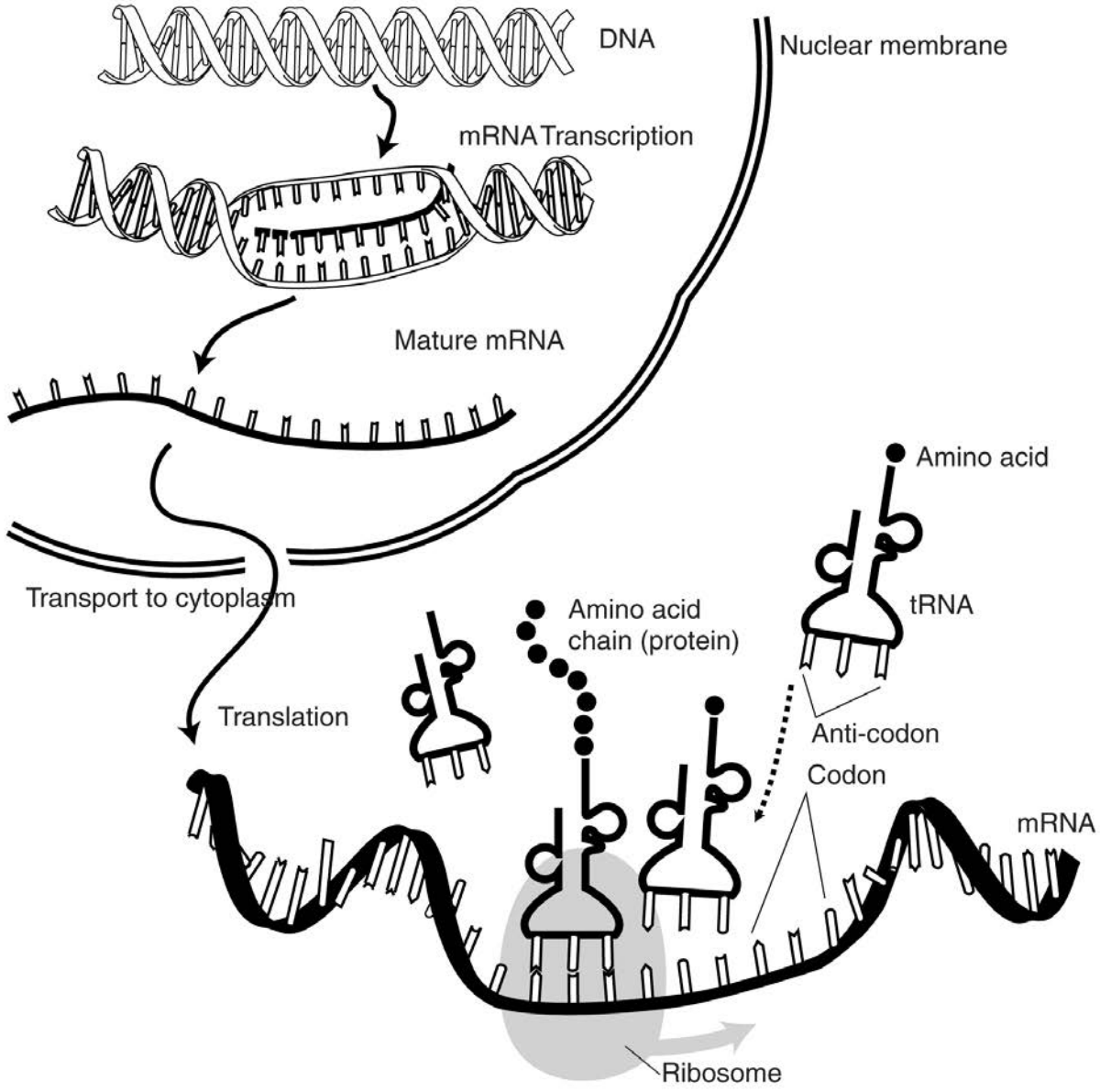

Figure 8.17: Summary of translation. Notice the mRNA segment within the ribosome. A tRNA anticodon binds to the appropriate codon, bringing the corresponding amino acid into the ribosome where it can be added to the growing polypeptide chain.

Many proteins undergo post-translational modification, allowing them to then perform their specific function. This may include the formation of disulfide bridges or attachment of any of a number of biochemical functional groups, such as phosphate groups, carbohydrates or lipids. Certain amino acids may be removed, or the polypeptide chain may be cut into two pieces. Lastly, two or more polypeptides may interact with each other, forming a functional protein with a quaternary structure.

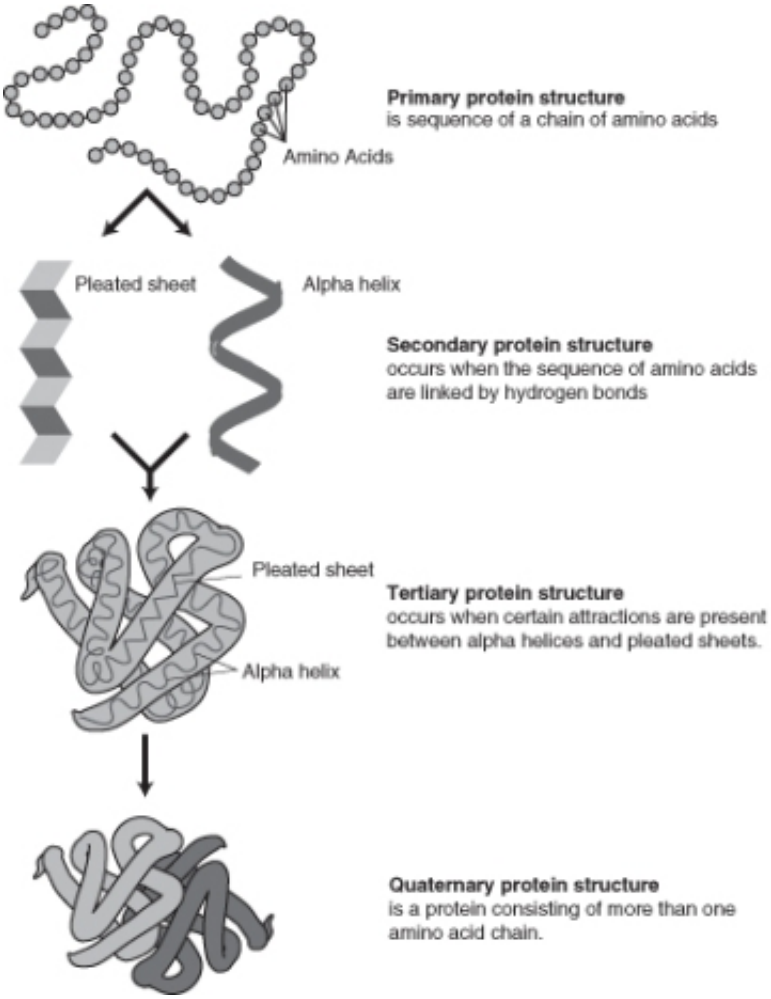

Figure 8.18: The four stages of protein folding.

Lesson Summary

- "DNA makes RNA makes protein" is the central dogma of molecular biology.
- Transcription is the transfer of the genetic instructions from DNA to RNA.
- Translation is the process of using the information in the mRNA to order amino acids into a polypeptide.

- Transcription begins with the binding of RNA polymerase to the promoter of a gene.
- Newly transcribed eukaryotic mRNA is not ready for translation; this mRNA requires extensive processing, including splicing and polyadenylation.
- A codon is a three base code for one amino acid.
- Start and stop codons signal the beginning and end of translation.
- There are three stop codons.
- The reading frame is the frame of three bases in which the mRNA is read.
- The genetic code is universal.
- Translation involves the interactions of the three types of RNA.
- After the protein is made, it must fold into its functional conformation.

Review Questions

1. What is meant by "DNA → RNA → Protein?"
2. Describe transcription.
3. List some of the modification mRNAs undergoes before translation.
4. Define introns and exons.
5. Describe mRNA splicing.
6. Describe the role of the Genetic Code in translation.
7. What is a reading frame?
8. Discuss what is meant by the universal genetic code.
9. Explain translation.
10. What is protein folding?

Further Reading / Supplemental Links

- Transcription Animation

http://www-class.unl.edu/biochem/gp2/m_biology/animation/gene/gene_a2.html

- Campbell, N.A. and Reece, J.B. *Biology*, Seventh Edition, Benjamin Cummings, San Francisco, CA, 2005.
- Biggs, A., Hagins, W.C., Kapicka, C., Lundgren, L., Rillero, P., Tallman, K.G., and Zike, D., *Biology: The Dynamics of Life*, California Edition, Glencoe Science, Columbus, OH, 2005.
- Nowicki S., *Biology*, McDougal Littell, Evanston, IL, 2008.
- The National Health Museum:

http://www.accessexcellence.org/RC/VL/GG/rna_synth.html

- Genetic Science Learning Center:

http://learn.genetics.utah.edu/units/basics/transcribe/

- Kimball's Biology Pages:

http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/C/Codons.html

- The National Health Museum:

http://www.accessexcellence.org/RC/VL/GG/genetic.html

- The National Health Museum:

http://www.accessexcellence.org/RC/VL/GG/protein_synthesis.html

- http://en.wikipedia.org

Vocabulary

5' cap A modified guanine nucleotide added to the 5'-end of the pre-mRNA; crucial for recognition and proper attachment of the mRNA to the ribosome.

A site Within the ribosome; binds a tRNA with an attached amino acid.

alternative splicing Process by which pre-mRNA messages can be spliced in several different configurations, allowing a single gene to encode multiple proteins.

E site Within the ribosome; contains the tRNA that no longer has an attached amino acid.

editing The process of changing the nucleotide sequence of an mRNA to allow the mRNA to produce multiple proteins.

elongation The segment of transcription that the further addition of RNA nucleotides; also refers to the process during translation of adding additional amino acids to the growing polypeptide chain.

exon The region of a gene that contains the code for producing a protein.

frameshift mutation Mutation that disrupt the reading frame by insertions or deletions of a non-multiple of three nucleotide bases.

gene A segment of DNA that contains the information necessary to encode an RNA molecule or a protein.

genetic code The code in which the language of nucleotides is used to create the language of amino acids.

initiation The start of transcription; signaled by the transcription initiation complex formed by the promoter, transcription factors, and RNA polymerase; also refers to the start of translation.

intron Long region of DNA that has no identified function; separates exons.

P site Within the ribosome; contains the tRNA with the growing polypeptide chain attached.

pre-mRNA Newly transcribed eukaryotic mRNA; not yet ready for translation.

polyadenylation The addition of a string of adenines to the mRNAs 3'-end; signals the termination of translation in eukaryotes.

reading frame The frame of three bases (codon) in which the mRNA is translated.

Rho-dependent termination Involves a protein factor (Rho), which destabilizes the RNA-DNA hybrid, releasing the newly synthesized mRNA from the elongation complex.

ribosome Non-membrane bound organelle; site of protein synthesis.

RNA polymerase The enzyme that reads a template strand of DNA during transcription to synthesize the complementary RNA strand.

splicing The process by which introns are removed from pre-mRNA.

spliceosome RNA-protein complex that usually performs splicing of the pre-mRNA.

termination The end of transcription; involves the detachment of the RNA from the DNA template; also refers to the end of translation when the ribosome comes to one of the three stop codons, for which there is no tRNA.

transcription The process that uses the DNA sequence to make an mRNA molecule.

translation The process of converting the language of nucleotides (in the mRNA) into the language of amino acids.

Points to Consider

We know what happens when everything goes right. The result is a correctly made protein that functions properly and maintains homeostasis.

- However, what happens when things do not go right? What can lead to a protein not being made correctly or not functioning correctly?
- Can you think of possible mechanisms that may that can interfere with protein synthesis?
- How can a change in the DNA sequence lead to a different protein?

8.3 Lesson 8.3: Mutation

Lesson Objectives

- Define mutation.
- Describe common causes of mutation.
- Describe common types of mutation.
- Illustrate common chromosomal alterations.
- Discuss potential outcomes of point mutations.
- List and describe three common types of point mutations.
- Discuss consequences of effect-on-function mutations.
- Discuss the significance of germline and somatic mutations.
- Explain why some mutations are harmful and some beneficial.
- Discuss the saying, "Without beneficial mutations, evolution can not occur."

Introduction

You have learned that an **allele** is an alternative form of a gene. Most, if not all genes have alternative forms causing the resulting protein to function slightly differently. But are there alleles that cause proteins to function dramatically differently or not function at all? A **mutation** is a change in the DNA or RNA sequence, and many mutations result in new alleles. Some of these changes can be beneficial. In fact, evolution could not take place without the genetic variation that results from mutations. But some mutations are harmful. There are also chromosomal mutations, large changes with dramatic effects.

Causes of Mutation

Is it possible for mutations to occur spontaneously, or does there have to be a cause of the mutation? Well, the answer is that both are possible. A spontaneous mutation can just

happen, possibly due to a mistake during DNA replication or transcription. Mutations may also occur during mitosis and meiosis. A mutation caused by an environmental factor, or **mutagen**, is known as an induced mutation. Typical mutagens include chemicals, like those inhaled while smoking, and radiation, such as X-rays, ultraviolet light, and nuclear radiation. **Table** 8.2 lists some spontaneous mutations that are common.

Table 8.2: **Common Spontaneous Mutations**

Tautomerism	a base is changed by the repositioning of a hydrogen atom
Depurination	loss of a purine base (A or G)
Deamination	spontaneous deamination of 5-methycytosine
Transition	a purine to purine, or a pyrimidine to pyrimidine change
Transversion	a purine becomes a pyrimidine, or vice versa

Types of Mutations

In multicellular organisms, mutations can be subdivided into germline mutations, which can be passed on to descendants, and somatic mutations, which cannot be transmitted to the next generation. Germline mutations change the DNA sequence within a sperm or egg cell, and therefore can be inherited. This inherited mutation may result in a class of diseases known as a genetic disease. The mutation may lead to a nonfunctional protein, and the embryo may not develop properly or survive. Somatic mutations may affect the proper functioning of the cell with the mutation. During DNA replication, the mutation will be copied. The two daughter cells formed after cell division will both carry the mutation. This may lead to the development of many cells that do not function optimally, resulting a less than optimal phenotype. Various types of mutations can all have severe effects on the individual. These include point mutations, framehift mutations and chromosomal alterations.

Keep in mind, some mutations may be beneficial or have no effect. Mutations that have no effect will not affect the expression of the gene or the sequence of amino acids in an encoded protein.

Chromosomal Alterations

Chromosomal alterations are large changes in the chromosome structure. They occur when a section of a chromosome breaks and rejoins incorrectly, or does not rejoin at all. Sometimes the segment may join backwards or reattach to another chromosome altogether. These mutations are very serious and usually lethal to the zygote or embryo. If the embryo

does survive, the resulting organism is usually sterile and thus, unable to pass along the mutation.

The five types of chromosomal alterations are deletions, duplications, insertions, inversions, and translocations (**Figure** 8.19).

1. **Deletions**: removal of a large chromosomal region, leading to loss of the genes within that region.
2. **Duplications** (or **amplifications**): lead to multiple copies of a chromosomal region, increasing the number of the genes located within that region. Some genes may be duplicated in their entirety.
3. **Insertions**: the addition of material from one chromosome to a nonhomologous chromosome.
4. **Inversions**: reversing the orientation of a chromosomal segment.
5. **Translocations**: interchange of genetic material between nonhomologous chromosomes.

Point Mutations

As the name implies, **point mutations** occur at a single site within the DNA. Lets go back to our earlier example from lesson 8.2:

THE BIG FAT CAT ATE THE RED RAT.

A change at any one position could result in a sequence that does not make sense. Such as:

THE BIG FAT SAT ATE THE RED RAT.

As shown above, point mutations exchange one nucleotide for another and are known as base substitution mutations. These mutations are often caused either by chemicals or by a mistake during DNA replication. A transition exchanges a purine for a purine (A G) or a pyrimidine for a pyrimidine, (C T), and is the most common point mutation. Less common is a transversion, which exchanges a purine for a pyrimidine or a pyrimidine for a purine (C/T A/G). Point mutations that occur within the protein coding region of a gene are classified by the effect on the resulting protein:

1. **Silent mutations**: which code for the same amino acid.
2. **Missense mutations**: which code for a different amino acid.
3. **Nonsense mutations**: which code for a premature stop codon.

These mutations may result in a protein with the same function, with altered function, or with no function. Silent mutations, as they code for the same amino acid, will have no altered effect on the protein. Missense mutations may have a minor effect or a dramatic

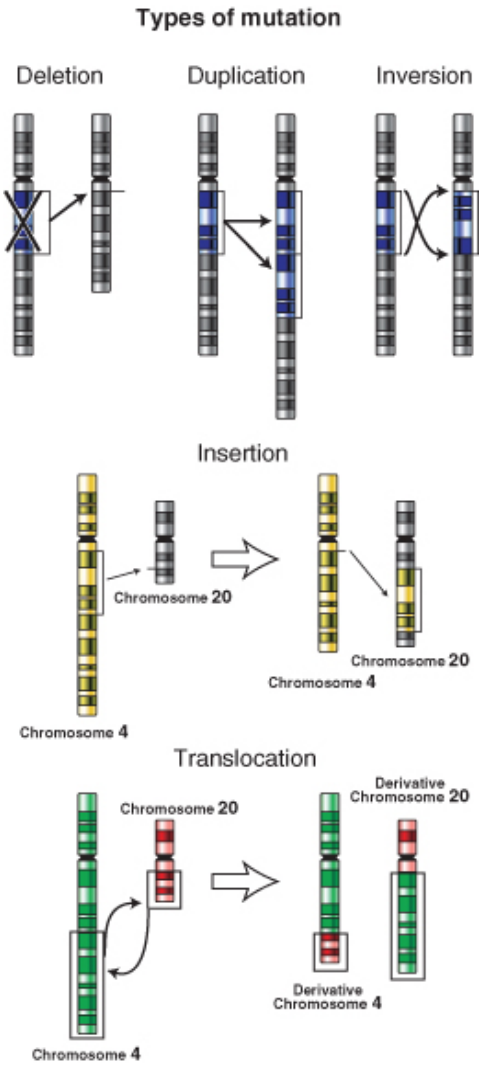

Figure 8.19: Chromosomal alterations. Deletion: the blue segment has been removed; Duplication: the blue segment has been duplicated; Inversions: the blue segment has been reversed; Insertion: the yellow segment has been removed from chromosome 4 and placed into chromosome 20; Translocation: a green segment from chromosome 4 has been exchanged with a red segment from chromosome 20.

effect on the protein. Nonsense mutations usually have the most dramatic effet. Depending on the position of the premature stop codon, nonsense mutations may result in an unstable mRNA that cannot be translated, or in a much "smaller" protein without any activity.

Deletions and Insertions

As pointed out earlier, a deletion or insertion in the DNA can alter the reading frame. **Deletions** remove one or more nucleotides from the DNA, whereas **insertions** add one or more nucleotides into the DNA. These mutations in the coding region of a gene may also alter splicing of the mRNA (splice site mutation). Mutations which alter the reading frame are known as **frameshift mutations**. **Splice site mutations** and frameshift mutations both can dramatically change the mRNA, altering the final protein product.

Effect-on-Function Mutations

For a cell or organism to maintain homeostasis, the proteins work in a highly defined and regulated manner. It may take just one protein not working correctly to interrupt homeostasis. A protein having more or less activity than normal, or a different activity or function, may be enough to interrupt homeostasis. Mutations that may result in altered function of the gene product or protein are loss-of-function and gain-of-function mutations, as well as dominant negative mutations.

Loss-of-function mutations result in a gene product or protein having less or no function. **Gain-of-function mutations** result in the gene product or protein having a new and abnormal function. **Dominant negative mutations** have an altered gene product that acts in a dominant manner to the wild-type gene product.

Significance of Mutation

Imagine the coding sequence (broken up into codons) TAC CCC GGG. This is a fairly generic coding sequence. It transcribes into the following mRNA: AUG GGG CCC, which would translate into start-glycine-proline. As glycine is encoded by four codons (GGG, GGA, GGC, GGU), any change in the third position of that codon will have no effect. The same is true for the codon for proline. But what about changes in the other nucleotides in the sequence? They could have potentially dramatic effects. The effects depend on the outcome of the mutation. Obviously any change to the start codon will interrupt the start of translation. Turning the simple glycine into the nonpolar (and relatively large) tryptophan (UGG codon) could have dramatic effects on the function of the protein.

Once again, a mutation is the change in the DNA or RNA sequence. As discussed earlier, in multicellular organisms, mutations can be subdivided into germline mutations and somatic mutations. **Germline mutations** occur in the DNA of sex cells, or gametes, and are

therefore potentially very serious. These mutations can be passed to the next generation. **Somatic mutations**, which occur in somatic, or body, cells, cannot be passed to the next generation (offspring). Mutations can be harmful, beneficial, or have no effect. If a mutation does not change the amino acid sequence in a protein, the mutation will have no effect. In fact, the overwhelming majority of mutations have no significant effect, since DNA repair mechanisms are able to mend most of the changes before they become permanent. Furthermore, many organisms have mechanisms for eliminating otherwise permanently mutated somatic cells.

A **gene pool** is the complete set of unique alleles in a species or population. Mutations create variation in the gene pool. Populations with a large gene pool are said to be genetically diverse and very robust. They are able to survive intense times of natural selection against certain phenotypes. During these times of selection, individuals with less favorable phenotypes resulting from deleterious alleles (due to mutations) may be selected against and removed from the population. Concurrently, the more favorable mutations that cause beneficial or advantageous phenotypes tend to accumulate in that population, resulting, over time, in evolution. We will discuss evolution and the genetic effects on evolution in much more detail in a later chapter.

Harmful Mutations

Mutations can result in errors in protein sequence, creating partially or completely nonfunctional proteins. These can obviously result in harm to the cell and organism. As discussed in the previous lesson, to function correctly and maintain homeostasis, each cell depends on thousands of proteins to all work together to perform the functions of the cell. When a mutation alters a protein that plays a critical role in the cell, the tissue, organ, or organ system may not function properly, resulting in a medical condition. A condition caused by mutations in one or more genes is called a **genetic disorder**, which will be discussed in the next chapter. However, only a small percentage of mutations cause genetic disorders; most have no impact on health. If a mutation does not change the protein sequence or structure, resulting in the same function, it will have no effect on the cell. Often, these mutations are repaired by the DNA repair system of the cell. Each cell has a number of pathways through which enzymes recognize and repair mistakes in DNA (**Figure** 8.20). Because DNA can be damaged or mutated in many ways, the process of DNA repair is an important way in which the cell protects itself to maintain proper function.

A mutation present in a germ cell can be passed to the next generation. If the zygote contains the mutation, every cell in the resulting organism will have that mutation. If the mutation results in a disease phenotype, the mutation causes what is called a hereditary disease. These will be discussed in the next chapter. On the other hand, a mutation that is present in a somatic cell of an organism will be present (by DNA replication and mitosis) in all descendants of that cell. If the mutation is present in a gene that is not used in that cell type, the mutation may have no effect. On the other hand, the mutation may lead to

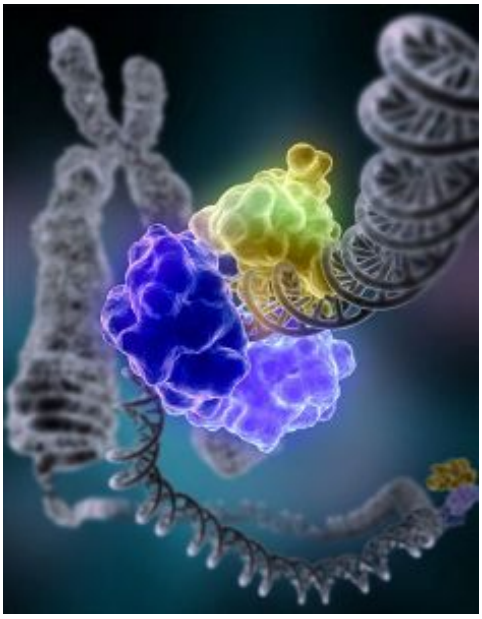

Figure 8.20: DNA repair. Shown is a model of DNA ligase repairing chromosomal damage. is an enzyme that joins broken nucleotides together by catalyzing the formation of a bond between the phosphate group and deoxyribose sugar of adjacent nucleotides in the DNA backbone.

a serious medical condition such as cancer. Mutations and cancer will be discussed in the next lesson.

Beneficial Mutations

A very small percentage of all mutations actually have a positive effect. These mutations lead to new versions of proteins that help an organism and its future generations better adapt to changes in their environment. The genetic diversity that results from mutations is essential for evolution to occur. Without genetic diversity, each individual of a species would be the same, and no one particular individual would have an advantage over another. Adaptation and evolution would not be possible. **Beneficial mutations** lead to the survival of the individual best fit to the current environment, which results in evolution. This will be discussed in the evolution chapter.

Mutations and Cancer

During the discussion of the cell cycle, cancer was described as developing due to unregulated cell division. That is, **cancer** is a disease characterized by a population of cells that grow and divide without respect to normal limits. These cancerous cells invade and destroy adjacent

tissues, and they may spread throughout the body.

Nearly all cancers are caused by mutations in the DNA of the abnormal cells. These mutations may be due to the effects of **carcinogens**, cancer causing agents such as tobacco smoke, radiation, chemicals, or infectious agents. These carcinogens may act as an environmental "trigger," stimulating the onset of cancer in certain individuals and not others. Do all people who smoke get cancer? No. Complex interactions between carcinogens and an individual's genome may explain why only some people develop cancer after exposure to an environmental trigger and others do not. Do all cancers need an environmental trigger to develop? No. Cancer causing mutations may also result from errors incorporated into the DNA during replication, or they may be inherited. Inherited mutations are present in all cells of the organism.

Oncogenes and Tumor Suppressor Genes

Mutations found in the DNA of cancer cells typically affect two general classes of genes: oncogenes and tumor suppressor genes. In "normal," non-cancerous cells, the products of **proto-oncogenes** promote cell growth and mitosis prior to cell division; thus, proto-oncogenes encode proteins needed for normal cellular functions. Mutations in proto-oncogenes can modify their expression and the function of the gene product, increasing the amount of activity of the product protein. When this happens, they become oncogenes; thus, the cells have a higher chance of dividing excessively and uncontrollably. Cancer-promoting **oncogenes** are often activated in cancer cells, giving those cells abnormal properties. The products of these genes result in uncontrolled cell growth and division, protection against programmed cell death, loss of respect for normal tissue boundaries, and the ability to become established in diverse tissue environments. Proto-oncogenes cannot be removed from the genome, as they are critical for growth, repair and homeostasis. It is only when they become mutated that the signals for growth become excessive.

In "normal" cells, the products of **tumor suppressor genes** temporarily discourage cell growth and division to allow cells to finish routine functions, especially DNA repair. Tumor suppressors are generally transcription factors, activated by cellular stress or DNA damage. The function of such genes is to stop the cell cycle in order to carry out DNA repair, preventing mutations from being passed on to daughter cells. However, if the tumor suppressor genes are inactivated, DNA repair cannot occur. Tumor suppressor genes can be inactivated by a mutation that either affects the gene directly or that affects the pathway that activates the gene. The consequence of the lack of DNA repair is that DNA damage accumulates, is not repaired, and inevitably leads to cancer.

Several Mutations to Cause Cancer

Typically, a series of several mutations in these genes that activate oncogenes and inactivate tumor suppressor genes is required to transform a normal cell into a cancer cell (**Figure** 8.21). Cells have developed a number of control mechanisms to overcome mutations in proto-oncogenes. Therefore, a cell needs multiple mutations to transform into a cancerous cell. A mutation in one proto-oncogene would not cause cancer, as the effects of the mutation would be masked by the normal control of mitosis and the actions of tumor suppressor genes. Similarly, a mutation in one tumor suppressor gene would not cause cancer either, due to the presence of many "backup" genes that duplicate its functions. It is only when enough proto-oncogenes have mutated into oncogenes and enough tumor suppressor genes have been deactivated that the cancerous transformation can begin. Signals for cell growth overwhelm the signals for growth regulation, and the cell quickly spirals out of control. Often, because many of these genes regulate the processes that prevent most damage to the genes themselves, DNA damage accumulates as one ages.

Usually, oncogenes are dominant alleles, as they contain gain-of-function mutations. Meanwhile, mutated tumor suppressors are generally recessive alleles, as they contain loss-of-function mutations. A proto-oncogene needs only a mutation in one copy of the gene to generate an oncogene; a tumor suppressor gene needs a mutation in both copies of the gene to render both products defective. There are instances when, however, one mutated allele of a tumor suppressor gene can render the other copy non-functional. These instances result in what is known as a **dominant negative effect**.

Lesson Summary

- Mutations may be due to environmental factors (mutagens) or may occur spontaneously.
- Typical mutagens include chemicals, such as those inhaled by smoking, and radiation, like X-rays, ultraviolet light, and nuclear radiation.
- Germline mutations can be passed on to descendants; somatic mutations cannot be transmitted to the next generation.
- Chromosomal alterations are large changes in the chromosome structure. There are 5 types of chromosomal alterations: deletions, duplications, insertions, inversions, and translocations.
- Point mutations occur at a single site within the DNA; examples of these include silent mutations, missense mutations, and nonsense mutations.
- A deletion or insertion in the DNA can alter the reading frame.
- Loss-of-function and gain-of-function mutations may result in altered function of the gene product or protein.
- Beneficial mutations may accumulate in a population, resulting, over time, in evolution.
- Harmful mutations can result in errors in protein sequence, creating partially or com-

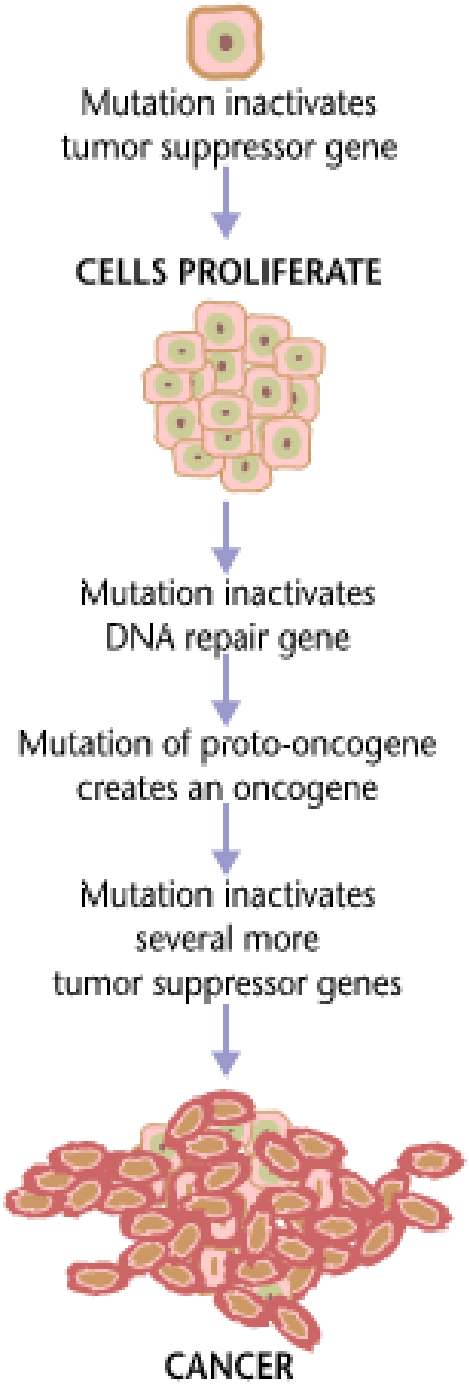

Figure 8.21: Cancers are caused by a series of mutations. Each mutation alters the behavior of the cell. In this example, the first mutation inactivates a tumor suppressor gene, the second mutation inactivates a DNA repair gene, the third mutation creates an oncogene, and a fourth mutation inactivates several more tumor suppressor genes, resulting in cancer. It should be noted that it does not necessarily require four or more mutations to lead to cancer.

pletely non-functional proteins.
- Nearly all cancers are caused by mutations in the DNA of the abnormal cells.
- In non-cancerous cells, proto-oncogenes promote cell growth and mitosis prior to cell division; thus, proto-oncogenes encode proteins needed for normal cellular functions.
- In non-cancerous cells, tumor suppressor genes temporarily discourage cell growth and division to allow cells to finish routine functions, especially DNA repair.
- Mutations in proto-oncogenes and tumor suppressor genes may lead to cancer.
- Usually mutations in multiple genes are necessary to develop cancer.

Review Questions

1. Define mutation.
2. What are some common causes of mutations?
3. List some common types of mutations.
4. Describe some common chromosomal alterations.
5. Discuss potential consequences of point mutations, deletions and insertions.
6. List and describe three common types of point mutations.
7. What are effect-on-function mutations?
8. What is a germline mutation? A somatic mutation?
9. Explain why some mutations are harmful and some beneficial.

Further Reading / Supplemental Links

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- Mutations and evolution:
- http://www.nwcreation.net/geneticrecombination.html
- http://en.wikipedia.org

Vocabulary

allele An alternative form of a gene.

beneficial mutation A mutation that leads to a new version of a protein that helps an organism and its future generations better adapt to changes in their environment.

cancer A disease characterized by a population of cells that grow and divide without respect to normal limits.

carcinogen Cancer causing agent, such as tobacco smoke, radiation, chemicals, or infectious agents.

chromosomal alterations Large changes in chromosome structure.

deamination A mutation due to the spontaneous deamination of 5-methycytosine.

deletion Removal of a large chromosomal region, leading to loss of the genes within that region; also the removal of one or more nucleotides from DNA.

depurination A mutation due to the loss of a purine base (A or G).

DNA ligase An enzyme that joins broken nucleotides together by catalyzing the formation of a bond between the phosphate group and deoxyribose sugar of adjacent nucleotides in the DNA backbone.

dominant negative mutation Mutation that results in an altered gene product that acts in a dominant manner to the wild-type gene product.

duplication Leads to multiple copies of a chromosomal region, increasing the number of the genes located within that region; also know as amplification.

frameshift mutation Mutations which alter the mRNA reading frame.

gain-of-function mutation Mutation that results in the gene product or protein having a new and abnormal function.

gene pool The complete set of unique alleles in a species or population.

genetic disorder A condition caused by mutations in one or more genes.

germline mutation Mutation in the DNA within a gamete; can be passed on to descendents.

insertion Chromosomal alteration involving the addition of material from one chromosome to a nonhomologous chromosome; also a mutation which adds one or more nucleotides into the DNA.

inversion Chromosomal alteration reversing the orientation of a chromosomal segment.

loss-of-function mutation Mutation that results in a gene product or protein having less or no function.

missense mutations Point mutation which codes for a different amino acid.

mutagen An environmental factor which causes a mutation; includes certain chemicals and radiation.

mutation A change in the DNA or RNA sequence.

nonsense mutation Point mutation which codes for a premature stop codon.

oncogene Cancer promoting gene; the products of these genes result in uncontrolled cell growth and division, protection against programmed cell death, loss of respect for normal tissue boundaries, and the ability to become established in diverse tissue environments.

point mutations Exchange one nucleotide for another; known as base substitution mutations.

proto-oncogenes Genes whose products promote cell growth and mitosis prior to cell division.

silent mutations Point mutation which codes for the same amino acid.

somatic mutation A mutation in a body cell, not in a gamete; cannot be transmitted to the next generation.

splice site mutation Mutation in the coding region of a gene that alters splicing of the mRNA.

tautomerism A mutation due to the changing of a base by the repositioning of a hydrogen atom.

transition A purine to purine, or a pyrimidine to pyrimidine change.

translocation Chromosomal alterations involving the interchange of genetic material between nonhomologous chromosomes.

transversion A purine is replaced by a pyrimidine, or a pyrimidine is replaced by a purine.

tumor suppressor gene Gene whose product temporarily discourage cell growth and division to allow cells to finish routine functions, especially DNA repair.

Points to Consider

- Now that we have discussed DNA, protein synthesis and mutations, can you think of a mechanism that allows different cell types to have different proteins?
- What about during development? Why does a developing embryo need different proteins at different times of development?
- We have discussed oncogenes and tumor suppressor genes. Can you think of a specific cellular mechanism in which defects in these genes lead to cancer?

8.4 Lesson 8.4: Regulation of Gene Expression

Lesson Objectives

- Describe general mechanisms of gene expression.
- Differentiate between a cis-regulatory element and a trans-acting factor.
- Define a transcription factor.
- Define an operon.
- Describe how the lac operon regulates transcription.
- Describe the role of the TATA box.
- Express the importance of gene regulation during development.
- Describe the role of homeobox genes and gap genes.
- Discuss gene regulation in terms of the development of cancer.

Introduction

Each of your cells has about 22,000 genes. In fact, all of your cells have the same genes. So do all of your cells make the same proteins? Do all 22,000 genes get turned into proteins in every cell? Of course not. If they did, then all your cells would do the same thing. You have cells with different functions because you have cells with different proteins. And your cells have different proteins because they "use" different genes. The regulation of gene expression,

or gene regulation, includes the mechanism to turn genes "on" and transcribe the gene into RNA. Any aspect of a gene's expression may be regulated, from the onset of transcription to the post-translational modification of a protein. It is this regulation that determines when and how much of a protein to make, giving a cell its specific structure and function.

Mechanisms of Regulation

Any step of gene expression may be modulated, from the DNA-RNA transcription step to post-translational modification of a protein. Following is a list of stages where gene expression is regulated:

- Chemical and structural modification of DNA or chromatin
- Transcription
- Translation
- Post-transcriptional modification
- RNA transport
- mRNA degradation
- Post-translational modifications

In this lesson, we will focus on regulation at the level of transcription. We have previously discussed that during transcription RNA polymerase reads the DNA template to make a complementary strand of RNA. The genes to which RNA polymerase binds is a highly regulated process. When RNA polymerase binds to a gene, it binds to the **promoter**, a segment of DNA that allows a gene to be transcribed. The promoter helps RNA polymerase find the start of a gene.

Gene regulation at the level of transcription controls when transcription occurs as well as how much RNA is created. This regulation is controlled by **cis-regulatory elements** and **trans-acting factors**. A cis-regulatory element is a region of DNA which regulates the expression of a gene or multiple genes located on that same strand of DNA. These cis-regulatory elements are often the binding sites of one or more trans-acting factors, usually a regulatory protein which interacts with RNA polymerase. A cis-regulatory element may be located in a gene's promoter region, in an intron, or in the 3' region.

A **regulatory protein**, or a **transcription factor**, is a protein involved in regulating gene expression. It is usually bound to a cis-regulatory element. Regulatory proteins often must be bound to a cis-regulatory element to switch a gene on (activator), or to turn a gene off (repressor).

Transcription of a gene by RNA polymerase can be regulated by at least five mechanisms:

- **Specificity factors** (proteins) alter the specificity of RNA polymerase for a promoter or set of promoters, making it more or less likely to bind to the promoter and begin transcription.

- **Repressors** (proteins) bind to non-coding sequences on the DNA that are close to or overlap the promoter region, impeding RNA polymerase's progress along the strand.
- **Basal factors**, transcription factors that help position RNA polymerase at the start of a gene.
- Enhancers are sites on the DNA strand that are bound by activators in order to loop the DNA, bringing a specific promoter to the initiation complex. An **initiation complex** is composed of RNA polymerase and trans-acting factors.
- **Activators** (proteins) that enhance the interaction between RNA polymerase and a particular promoter.

As the organism grows more sophisticated, gene regulation becomes more complex, though prokaryotic organisms possess some highly regulated systems. Some human genes are controlled by many activators and repressors working together. Obviously, a mutation in a cis-regulatory region, such as the promoter, can greatly affect the proper expression of a gene. It may keep the gene permanently off, such that no protein can be made, or it can keep the gene permanently on, such that the corresponding protein is constantly made. Both of these can have detremental effects on the cell.

Prokaryotic Gene Regulation

In prokaryotes, a combination of activators and repressors determines whether a gene is transcribed. As you know, prokaryotic organisms are fairly simple organisms with much less DNA. Prokaryotic genes are arranged in **operons**, a region of DNA with a promoter, an operator (defined below), and one or more genes that encode proteins needed to perform a certain task. To maintain homeostasis (and survive), the organism must quickly adapt changing environmental conditions. The regulation of transcription plays a key role in this process.

For a bacteria, many aspects of gene regulation are due to the presence or absence of certain nutrients. In prokaryotes, repressors bind to regions called **operators** that are generally located immediately downstream from the promoter. Activators bind to the upstream portion of the promoter.

The Lac Operon

The **lac operon** (**Figure** 8.22) is an operon required for the transport and metabolism of lactose in *E. coli*. The lac operon is regulated by the availability of lactose. The lac operon consists of a promoter, an operator, three adjacent structural genes which code for enzymes and a terminator. The three genes are: lacZ, lacY, and lacA. All three genes are controlled by the same regulatory elements.

In bacteria, the lac repressor protein blocks the synthesis of enzymes that digest lactose when

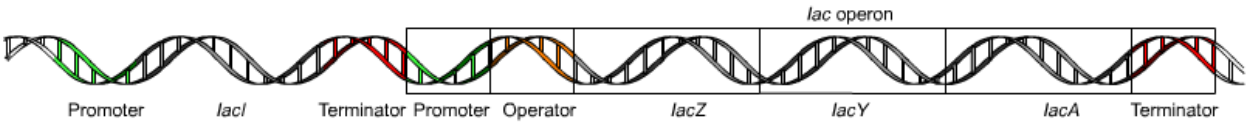

Figure 8.22: The lac operon. The lac operon contains genes for three enzymes, lac, lacY, and lac A, as well as the promoter, operator, and terminatory regulatory regions.

there is no lactose present (**Figure** 8.23). When lactose is present, it binds to the repressor, causing it to detach from the DNA strand.

Specific control of the lac operon depends on the availability of lactose. The enzymes needed to metabolize lactose are not produced when lactose is not present. When lactose is available, and therefore needs to be metabolized, the operon is turned on, RNA polymerase binds to the promoter, and the three genes are transcribed into a single mRNA molecule. However, if lactose is not present (and therefore does not need to be metabolized), the operon is turned off by the lac repressor protein (**Figure** 8.23).

The lacI gene, which encodes the lac repressor, lies near the lac operon and is always expressed (constitutive). Therefore, the lac repressor protein is always present in the bacteria. In the absence of lactose, the lac repressor protein will bind to the operator, just past the promoter in the lac operon. The repressor blocks the binding of RNA polymerase to the promoter, keeping the operon turned off (**Figure** 8.23).

When lactose is available, a lactose metabolite called allolactose binds to the repressor. This interaction causes a conformational change in the repressor shape and the repressor falls off the operator, allowing RNA polymerase to bind to the promoter and initiate transcription (**Figure** 8.23).

Eukaryotic Gene Regulation

As previously discussed, all your cells have the same DNA (and therefore the same genes), yet they have different proteins because they express different genes. In eukaryotic cells, the start of transcription is one of the most complex aspects of gene regulation. Transcriptional regulation involves the formation of an initiation complex involving interactions between a number of transcription factors, *cis*-regulatory elements, and **enhancers**, distant regions of DNA that can loop back to interact with a gene's promoter. These regulatory elements occur in unique combinations within a given cell type, resulting in only necessary genes being transcribed in certain cells. Transcription factors bind to a DNA strand, allowing RNA polymerase to bind and start transcription.

Each gene has unique cis-regulatory sequences, only allowing specific transcription factors to bind. However, there are common regulatory sequences found in most genes. The **TATA box** is a *cis*-regulatory element found in the promoter of most eukaryotic genes. It has the

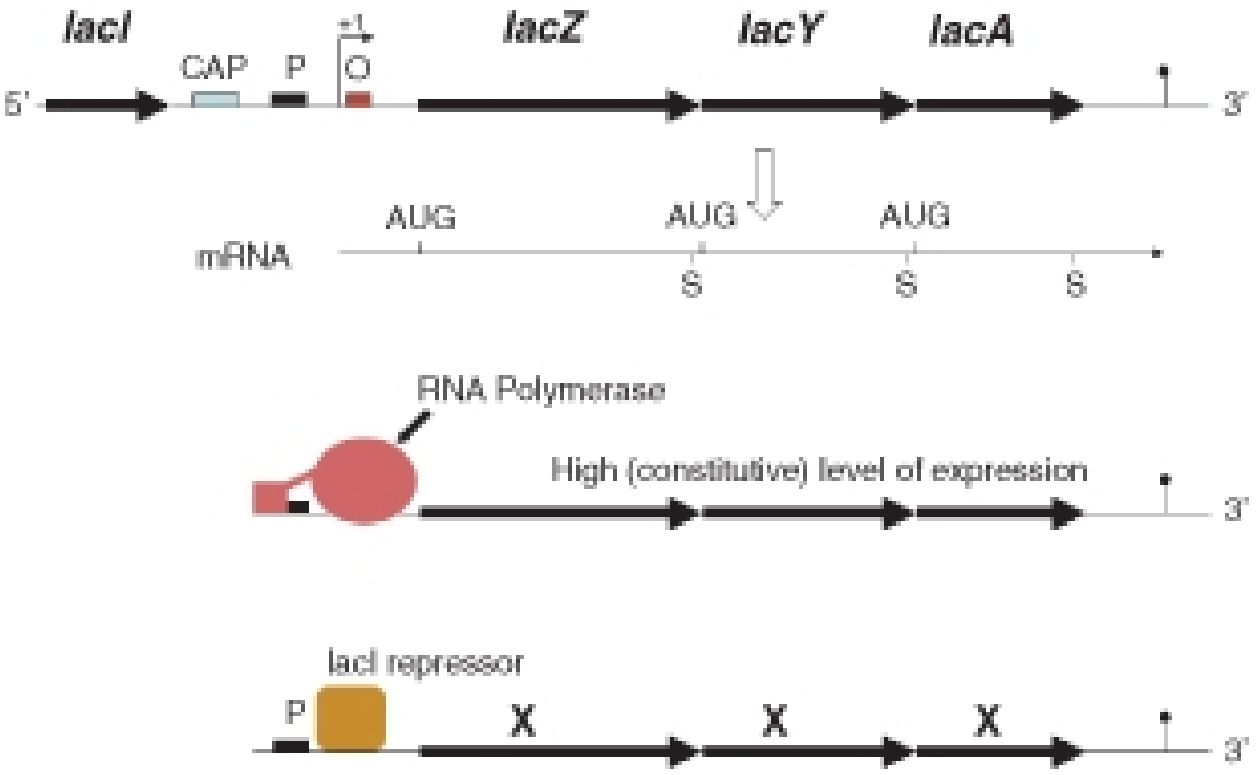

Figure 8.23: Regulation of the lac operon. When lactose is present, (red) binds to the promoter (P) and the three genes are expressed, producing a single mRNA for the three genes. When lactose is unavailable, the lac repressor (yellow) binds to the operator (O) and inhibits the binding of RNA polymerase to the promoter. The three genes are not expressed. For an animation of the Lac Operon, see

DNA sequence 5'-TATAAA-3' or a slight variant, and has been highly conserved throughout evolution. When the appropriate cellular signals are present, RNA polymerase binds to the TATA box, completing the initiation complex. A number of transcription factors first bind to the TATA box while other transcription factors bind to the previously attached factors, forming a multi-protein complex. It is only when all the appropriate factors are bound that RNA polymerase will recognize the complex and bind to the DNA, initiating transcription.

One of the more complex eukaryotic gene regulation processes is during development. What genes must be turned on during development so that tissues and organs form from simple cells?

Regulation of Gene Expression During Development

What makes the heart form during development? What makes the skin form? What makes a structure become an arm instead of a leg? These processes occur during development because of a highly specific pattern of gene expression. This intensely regulated pattern of gene expression turns genes on in the right cell at the right time, such that the resulting proteins can perform their necessary functions to ensure proper development. Transcription factors play an extremely important role during development. Many of these proteins can be considered master regulatory proteins, in the sense that they either activate or deactivate the transcription of other genes and, in turn, these secondary gene products can regulate the expression of still other genes in a regulatory cascade. Homeobox and gap genes are important transcription factors during development.

Homeobox Genes

Homeobox genes contain a highly conserved DNA sequence known as a homeobox and are involved in the regulation of genes important to development. A homeobox is about 180 base pairs long; it encodes a 60 amino acid domain within the protein (known as the homeodomain), which can bind DNA. Proteins with a homeodomain are therefore transcription factors. These factors typically switch on series of other genes, for instance, the genes needed to encode the proteins to make a leg.

A particular subgroup of homeobox genes are the **Hox genes**. Protein products of Hox genes function in patterning the body, providing the placement of certain body parts during development. In other words, Hox genes determine where limbs and other body segments will grow in a developing fetus or larva. Mutations in any one of these genes can lead to the growth of extra, typically non-functional body parts in invertebrates. The Antennapedia mutation in *Drosophila* results in a leg growing from the head in place of an antenna. A mutation in a vertebrate Hox genes usually results in miscarriage.

Gap Genes

A **gap gene** controls the shape of a developing zygote early in its development. The products of these genes produce gaps in a rather uniform arrangement of cells (**Figure** 8.24). One example of this is the Kruppel gene, which regulates the activity of a number of other genes. Gap genes encode transcription factors, and the Kruppel gene is a zinc-finger protein. A **zinc finger** is a DNA binding region within the protein. A zinc finger consists of two antiparallel sheets and an helix with a zinc ion, which is important for the stability of this region. Gap genes control the expression of other genes within specific regions of cells in the developing organism. This allows specific genes to be expressed in certain cells at the appropriate stage of development.

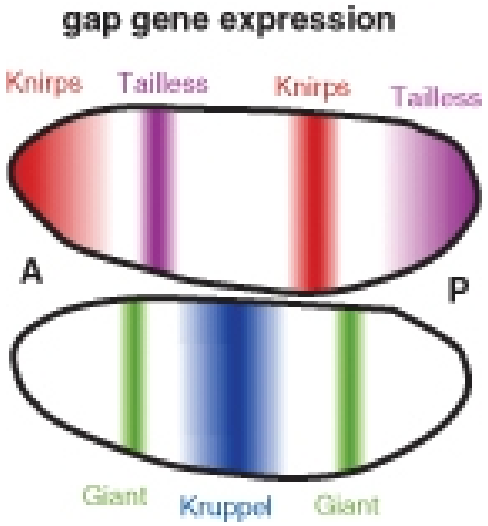

Figure 8.24: Gap gene expression. Shown is the expression pattern of four gap genes, Kruppel, Giant, Knirps, and Tailless, in a developing embryo. Note how the expression of these genes creates an unique pattern resulting in gaps in what was a rather uniform arrangement of cells.

Regulation of Gene Expression in Cancer

As discussed in the last lesson, carcinogenesis depends on both the activation of oncogenes and deactivation of tumor suppressor genes. At least two separate mutations are necessary to develop cancer. For example, a mutation in a proto-oncogene would not necessarily lead to cancer, as normally functioning tumor suppressor genes would counteract the effects of the oncogene. It is the second mutation in the tumor suppressor gene that could lead to uncontrolled cell growth and possibly cancer. Both oncogenes and tumor suppressor genes play an important role in gene regulation and cell proliferation (**Figure** 8.25).

Oncogenes

The products of proto-oncogenes are required for normal growth, repair and homeostasis. However, when these genes are mutated, they turn into oncogenes and play a role in the development of cancer. Proto-oncogenes may be growth factors, transcription factors, or other proteins involved in regulation. A very common oncogene, ras, is normally a regulatory GTPase that switches a signal transduction chain on and off. Ras and Ras-related proteins are products of oncogenes found in 20% to 30% of human tumors.

Ras is a **G protein**, a regulatory GTP hydrolase that cycles between an activated and inactivated form. When a growth factor binds to its receptor on the outside of the cell, a signal is relayed to RAS. As a G protein, Ras is activated when GTP is bound to it. The active Ras then passes the signal to a series of protein kinases, regulatory proteins that eventually activate transcription factors to alter gene expression and produce proteins that stimulate the cell cycle (**Figure** 8.25). Many of the genes and proteins involved in signal transduction pathways are interconnected to ras. Any mutation that makes ras more active or otherwise interrupts the normal signal transduction pathways (**Figure** 8.25) may result in excessive cell division and cancer.

Tumor Suppressor Genes

An example of a tumor suppressor gene is p53, which encodes a 53,000 dalton protein, The p53 gene is activated by DNA damage. DNA may be damaged by ultraviolet light, and any damaged DNA may be harmful to the cell. Mutations causing problems with any of the components of **Figure** 8.25 may lead to the development of cancer. So that damaged DNA is not replicated, the cell cycle must be temporarily stopped so that the DNA can be repaired. The p53 tumor suppressor gene encodes a transcription factor that regulates the synthesis of cell cycle inhibiting proteins (**Figure** 8.25). p53 often activates a gene named p21, whose protein product temporarily stops the cell cycle. If the DNA can not be repaired, p53 activates other genes that lead to cell death, or apoptosis. This prevents the cell from passing on damaged DNA. If the p53 tumor suppressor gene is defective, as by mutation, DNA damage in the cell may accumulate and the cell may survive to replicate the damaged DNA. The damaged DNA would then be passed to other cells through many cell divisions, and cancer could develop.

Lesson Summary

- A cis-regulatory element is a region of DNA which regulates the expression of a gene or multiple genes located on that same strand of DNA.
- The cis-regulatory elements are often binding sites for one or more trans-acting factors, usually a regulatory protein which interacts with RNA polymerase.
- Repressor proteins bind to non-coding sequences on the DNA that are close to or

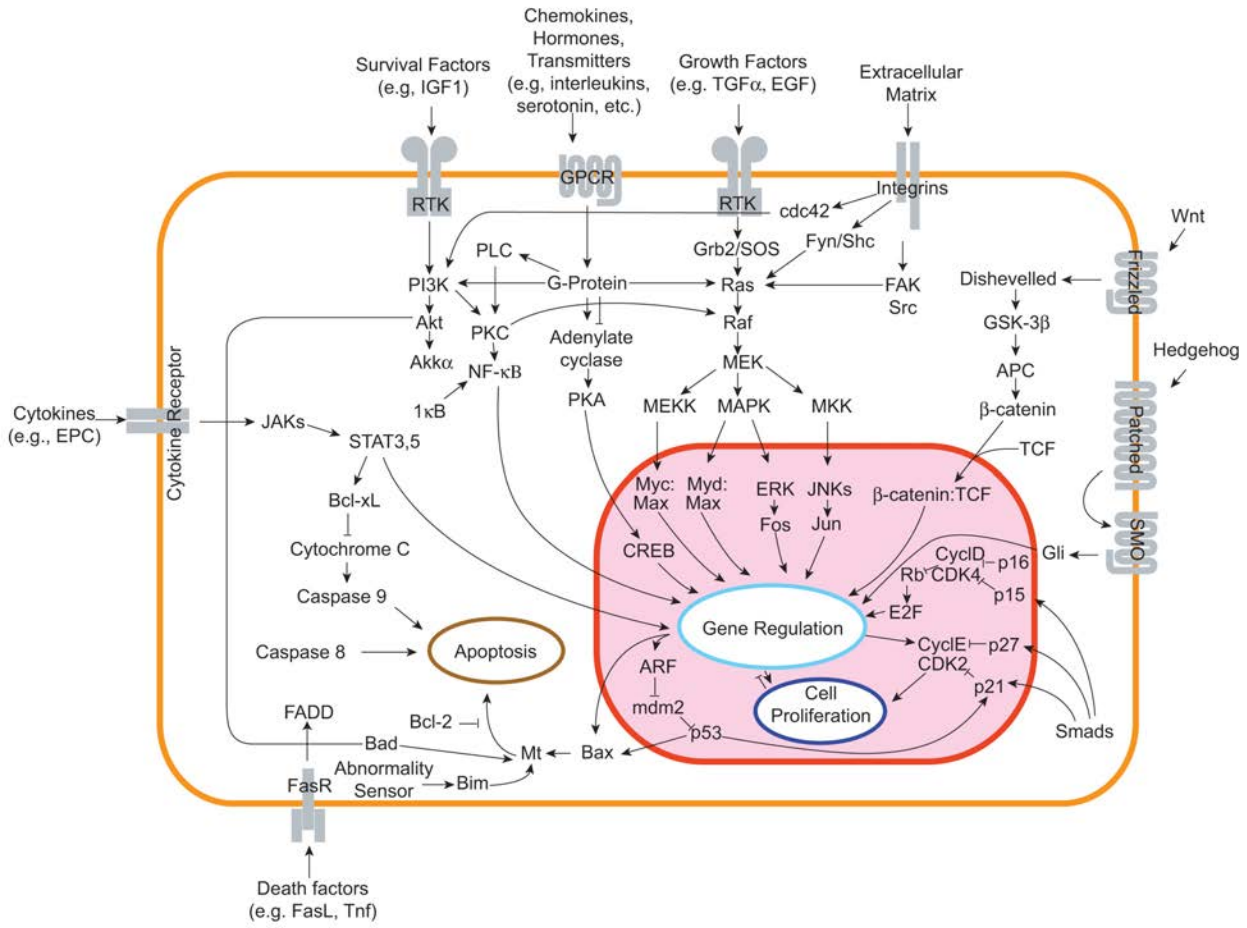

Figure 8.25: Signal transduction pathways. Ras (upper middle section) activates a number of pathways but an especially important one seems to be the mitogen-activated protein kinases (MAPK). MAPK transmit signals downstream to other protein kinases and gene regulatory proteins. Note that many of these pathways are initiated when a signal binds to its receptor outside the cell. Most pathways end with altered gene regulation and cell proliferation. The p53 tumor suppressor protein is shown at the lower section of the figure stimulating p21. The complexity of the pathways demonstrate the significant role these play in the cell.

overlap the promoter region, impeding RNA polymerase's progress along the strand.
- Enhancers are sites on the DNA strand that are bound by activators.
- Prokaryotic genes are arranged in operons, regions of DNA with a promoter, an operator, and one or more genes that encode proteins needed to perform a certain task.
- The regulation of the lac operon is a key example of prokaryotic gene regulation. When lactose is present, RNA polymerase binds to the promoter and the operon is turned on; when lactose is unavailable, the lac repressor binds to the operator and the operon is turned off.
- Homeobox genes are involved in the regulation of genes important to development. They encode transcription factors.
- Gap genes control the shape of a developing zygote early in its development.
- At least two separate mutations are necessary to develop cancer. These mutations may occur in proto-oncogenes and/or tumor suppressor genes.

Review Questions

1. What is meant by gene expression, and why is this an important cellular mechanism?
2. How do cis-regulatory elements and a trans-acting factors work together?
3. Define a transcription factor.
4. Define an operon. Give an example.
5. Describe how the lac operon regulates transcription.
6. Describe the role of the TATA box.
7. Why is gene regulation an important aspect of development?
8. What is a homeobox gene? A gap gene? Why are these genes important?
9. Why does altered gene regulation have a potential role in the development of cancer?

Further Reading / Supplemental Links

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- Biggs, A., Hagins, W.C., Kapicka, C., Lundgren, L., Rillero, P., Tallman, K.G., and Zike, D., *Biology: The Dynamics of Life*, California Edition, Glencoe Science, Columbus, Oh, 2005.
- Nowicki S., *Biology*, McDougal Littell, Evanston, IL, 2008.
- http://en.wikipedia.org

Vocabulary

activator Protein that enhances the interaction between RNA polymerase and a particular promoter.

basal factor Transcription factor that helps position RNA polymerase at the start of a gene.

cis-regulatory element A region of DNA which regulates the expression of a gene or multiple genes located on that same strand of DNA.

enhancer Site on the DNA strand that can be bound by activator(s) in order to loop the DNA, bringing a specific promoter to the initiation complex.

G protein A regulatory GTP hydrolase that cycles between an activated and inactivated form; activated when GTP is bound to it.

gap gene Gene that controls the shape of a developing zygote early in its development; encodes transcription factors.

homeobox A 180 base pair long highly conserved segment of DNA; encodes a 60 amino acid domain within the protein (known as the homeodomain), which can bind DNA.

homeobox genes Genes that contain a highly conserved DNA sequence known as a homeobox and are involved in the regulation of genes important to development; encodes transcription factors.

hox genes Genes that function in patterning the body, providing the placement of certain body parts during development.

initiation complex Complex needed to start transcription in eukaryotes; composed of RNA polymerase and trans-acting factors.

lac operon An operon required for the transport and metabolism of lactose in *E. coli*.

operator A region of prokaryotic DNA where a repressors binds.

operon A region of prokaryotic DNA with a promoter, an operator, and one or more genes that encode proteins needed to perform a certain task.

promoter A segment of DNA that allows a gene to be transcribed; helps RNA polymerase find the start of a gene.

repressor Protein that binds to non-coding sequences on the DNA that are close to or overlap the promoter region, impeding RNA polymerase's progress along the strand.

RNA polymerase The enzyme that transcribes the DNA to make RNA.

specificity factor Protein that alters the specificity of RNA polymerase for a promoter or set of promoters, making it more or less likely to bind to the promoter and begin transcription.

TATA box A *cis*-regulatory element found in the promoter of most eukaryotic genes; when the appropriate cellular signals are present, RNA polymerase binds to the TATA box, completing the initiation complex.

transcription factor A protein involved in regulating gene expression; usually bound to a cis-regulatory element; also known as a regulatory protein.

zinc finger A DNA binding region within certain proteins encoded by a gap gene; consists of two antiparallel sheets and an helix with a zinc ion, which is important for the stability of this region.

Points to Consider

- The next chapter is *Human Genetics*. Discuss why an understanding of human genetics is an important medical issue for our society.
- We have extensively discussed mutations and cancer. There are many other phenotypes due to mutations in the human genome. Why is understanding mutations in humans important?
- What do you think the Human Genome Project is? What could some implications of The Human Genome Project be?

Image Sources

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(2) *Summary of translation.*. Public Domain.

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2.5,Public Domain.

(23) http://en.wikipedia.org/wiki/Image:Griffith_experiment.svg. GNU-FDL.

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Chapter 9

Human Genetics

9.1 Lesson 9.1: Human Chromosomes and Genes

Lesson Objectives

- What is a genetic disease?
- What is the human genome?
- Discuss the importance of characterizing the human genome.
- Define autosome and sex-chromosome.
- Discuss the importance of SNPs.
- What is a karyotype?
- Define sex-linked and X-inactivation.

Introduction

As has been previously discussed, genetics is the branch of biology that focuses on heredity. The basics of heredity are similar for all organisms that reproduce sexually: the offspring receive one set of genetic material from one parent and the other set from the other parent. But are there aspects of genetics that are specific for us? Let's find out.

A **genetic disease** is a phenotype due to a mutation in a gene or chromosome. Many of these mutations are present at conception and are therefore in every cell of the body. Mutant alleles may be inherited from one or both parents, resulting in a dominant or recessive hereditary disease. Currently, there are over 4,000 known genetic disorders, with many more phenotypes yet to be identified. Theoretically, every human gene, when disrupted due to a mutation, could result in at least one disease-type phenotype. Genetic diseases are typically diagnosed and treated by a **geneticist**, a medical doctor specializing in these disorders, many of which are extremely rare and difficult to diagnose. Individuals and families with genetic diseases, or

suspected genetic diseases, are often counseled by **genetic counselors**, individuals trained in human genetics and counseling. To understand human genetic diseases, you first need to understand human chromosomes and genes.

The Human Genome

What makes each one of us unique? You could argue that the environment plays a role, and it does to some extent. But most would agree that your parents have something to do with your uniqueness. In fact, it is our genes that make each one of us unique – or at least genetically unique. We all have the genes that make us human: the genes for skin and bones, eyes and ears, fingers and toes, and so on. However, we all have different skin colors, different bone sizes, different eye colors and different ear shapes. In fact, even though we have the same genes, the products of these genes work a little differently in most of us. And that is what makes us unique.

The human genome is the genome - all the DNA - of *Homo sapiens*. Humans have about 3 billion bases of information, divided into roughly 20,000 genes, which are spread among non-coding sequences and distributed among 24 distinct chromosomes (22 autosomes plus the X and Y sex chromosomes) (**Figure** 9.1). The **genome** is all of the hereditary information encoded in the DNA, including the genes and non-coding sequences. The Human Genome Project (See the *Biotechnology* chapter) has produced a reference sequence of the human genome. The human genome consists of protein-coding exons, associated introns and regulatory sequences, genes that encode other RNA molecules, and "junk" DNA, regions in which no function as yet been identified.

Chromosomes and Genes

The human genome consists of 24 distinct chromosomes: 22 autosomal chromosomes plus the sex-determining X and Y chromosomes. A chromosome is a threadlike molecule of genes and other DNA located in the nucleus of a cell. Different organisms have different numbers of chromosomes. Human somatic cells have 23 chromosome pairs for a total of 46 chromosomes: two copies of the 22 autosomes (one from each parent), plus an X chromosome from the mother and either an X or Y chromosome from the father (**Figure** 9.2).

There are an estimated 20,000 human protein-coding genes, but many more proteins. Most human genes have multiple exons separated by much larger introns. Regulatory sequences controlling gene expression are associated with exon sequences. The introns are usually excised (removed) during post-transcriptional modification of the mRNA. Human cells make significant use of alternative splicing (see the *Molecular Genetics* chapter) to produce a number of different proteins from a single gene. So even though the human genome is surprisingly similar in size to the genomes of simpler organisms, the human proteome is thought to be much larger. A **proteome** is the complete set of proteins expressed by a

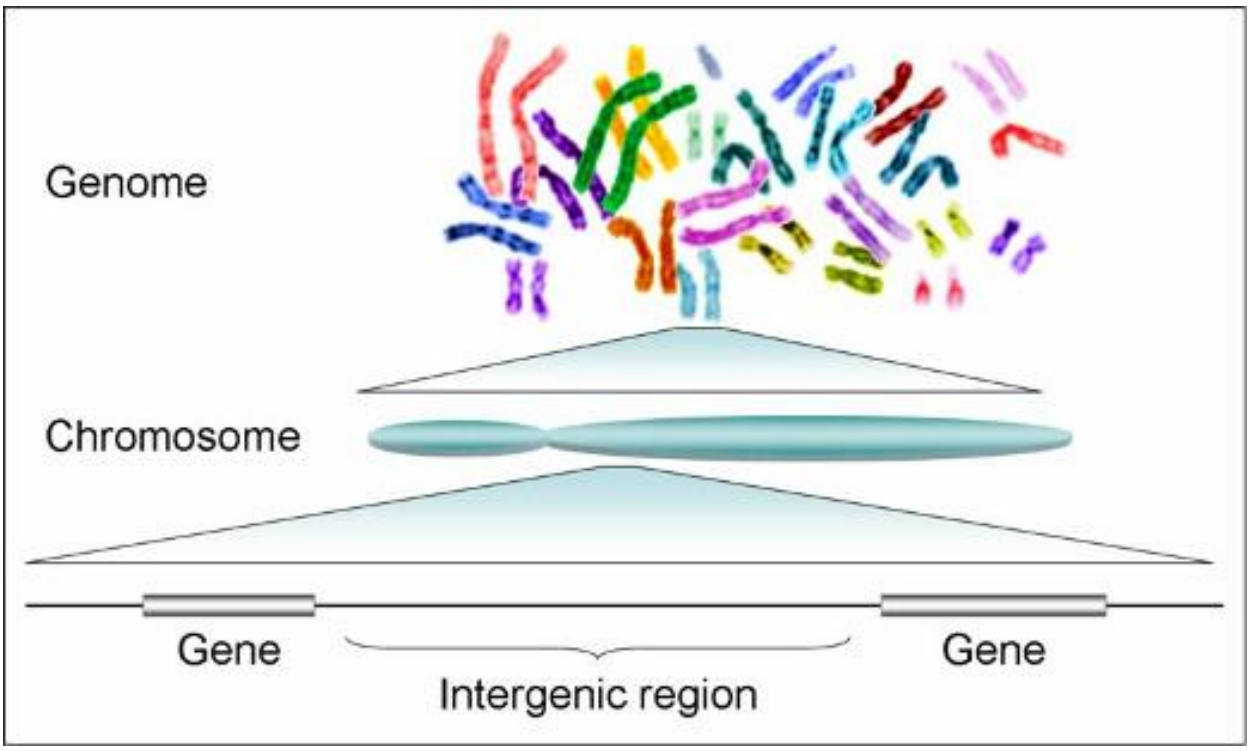

Figure 9.1: The Human Genome is depicted as the stained chromosomes at the top of the figure. The genome consists of chromosomes, which are composed of genes and other regions of DNA between the genes. Notice that there are 23 pairs of chromosomes.

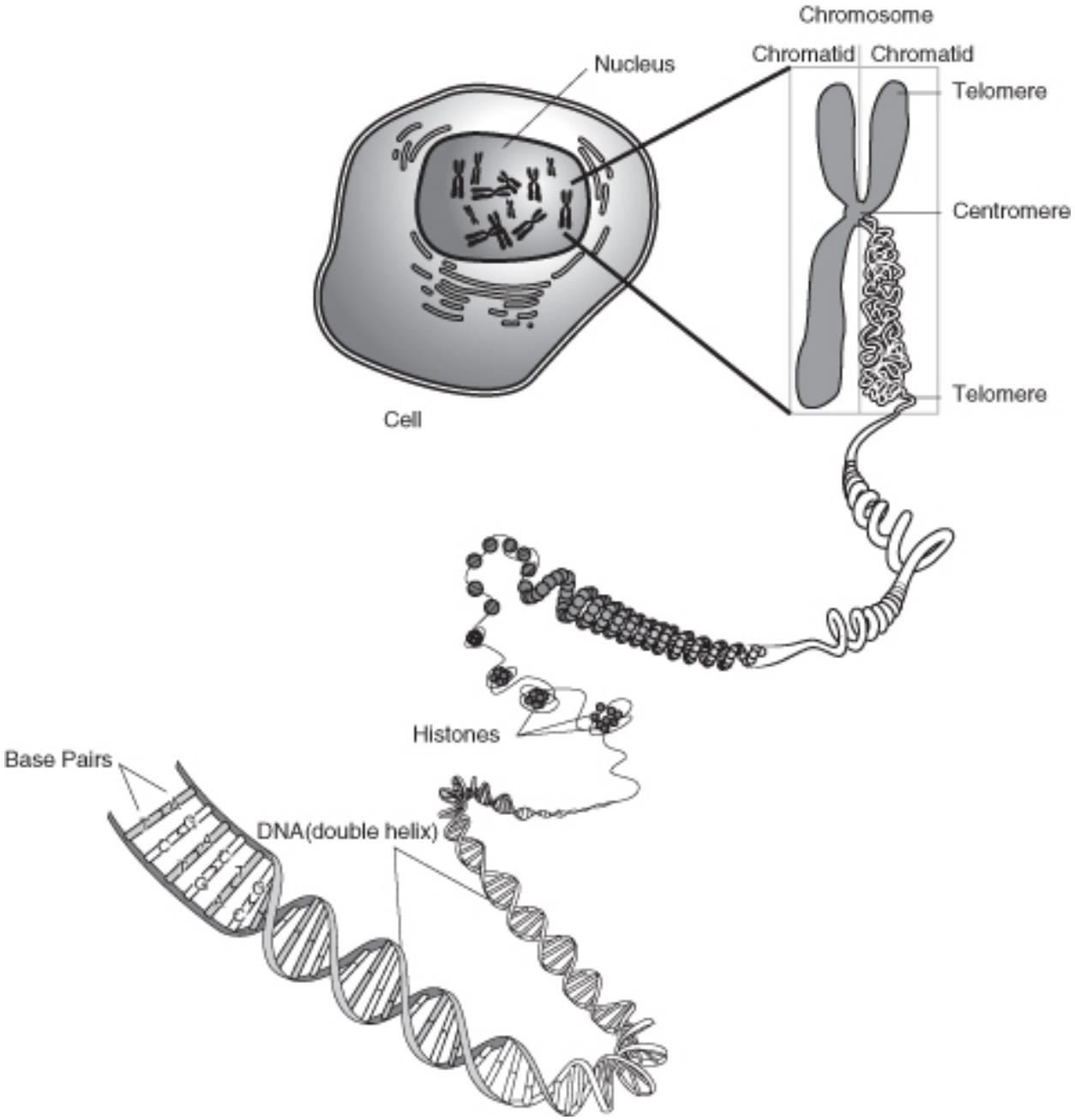

Figure 9.2: The human genome has 23 pairs of chromosomes located in the nucleus of somatic cells. Each chromosome is composed of genes and other DNA wound around histones (proteins) into a tightly coiled molecule.

genome, cell, tissue, or organism.

Linkage

As stated above, our roughly 20,000 genes are located on 24 distinct chromosomes. **Linkage** refers to particular genetic loci, or alleles inherited together, suggesting that they are physically on the same chromosome, and located close together on that chromosome. Two or more loci that are on the same chromosome are physically connected and tend to segregate together during meiosis, unless a cross over event occurs between them. A crossing-over event during prophase I of meiosis is rare between loci that usually segregate together; these loci will usually be close together on the same chromosome. They are, therefore, said to be linked. Alleles for genes on different chromosomes are not linked; they sort independently (independent assortment) of each other during meiosis.

A gene is also said to be linked to a chromosome if it is physically located on that chromosome. For example, a gene (or loci) is said to be linked to the X-chromosome if it is physically located on the X-chromosome chromosome. The physical location of a gene is important when analyzing the inheritance patterns of phenotypes due to that gene. The inheritance patterns of phenotypes may be different if the gene is located on a sex chromosome or an autosome. This will be further discussed in the next lesson.

Linkage Maps

The frequency of recombination refers to the rate of crossing-over (recombination) events between two loci. This frequency can be used to estimate genetic distances between the two loci, and create a **linkage map**. In other words, the frequency can be used to estimate how close or how far apart the two loci are on the chromosome.

In the early 20^{th} century, Thomas Hunt Morgan, working with the fruit fly *Drosophila Melanogaster*, demonstrated that the amount of crossing over between linked genes differs. This led to the idea that the frequency of crossover events would indicate the distance separating genes on a chromosome. Morgan's student, Alfred Sturtevant, developed the first genetic map, also called a linkage map.

Sturtevant proposed that the greater the distance between linked genes, the greater the chance that non-sister chromatids would cross over in the region between the genes during meiosis. By determining the number of recombinants - offspring in which a cross-over event has occured - it is possible to determine the approximate distance between the genes. This distance is called a genetic map unit (m.u.), or a **centimorgan**, and is defined as the distance between genes for which one product of meiosis in 100 products is a recombinant. So, a recombinant frequency of 1% (1 out of 100) is equivalent to 1 m.u. Loci with a recombinant frequency of 10% would be separated by 10 m.u. The recombination frequency will be 50% when two genes are widely separated on the same chromosome or are located on

different chromosomes. This is the natural result of independent assortment. Linked genes have recombination frequencies less than 50%.

Determining recombination frequencies between genes located on the same chromosome allows a linkage map to be developed. Linkage mapping is critical for identifying the location of genes that cause genetic diseases.

Variation

As stated above, even though we essentially all have the same genes, the gene products work a little different in all of us, making us unique. That is, the variation within the human genome results in the uniqueness of our species. In fact, genetically speaking, we are all about 99.9% identical. However, it is this 0.1% variation that results in our physical noticeable differences, as well as traumatic events such as illnesses or congenital deformities. These differences can also be used for societies benefits, such as through forensic DNA analysis (discussed in the *Biotechnology* chapter). Most studies of this genetic variation focus on small differences, know as **SNPs**, or **single nucleotide polymorphisms**, which are substitutions in individual bases along a chromosome. For example, the single base change from the sequence GGATAACGTCA to GGAAAACGTCA would be a SNP. Although not occurring uniformly, in the human genome, it has been estimated that SNPs occur every 1 in 100 to 1 in 1000 bases.

DNA sequences that repeat a number of times are known as **repetitive sequences** or repetitive elements. For example the sequence CACACACACACACA would be a dinucleotide (2 base) repeat, or the sequence GATCGATCGATCGATCGATC would be a tetranucleotide (4 base) repeat. The genomic loci and length of certain types of repetitive sequences are highly variable from person to person, which is the basis of DNA fingerprinting and DNA paternity testing technologies. Longer repetitive elements are also common in the human genome. Examples of repeat polymorphisms are described in **Table** 9.1

Table 9.1: **Repeat Polymorphisms (bp = base pair)**

Dinucleotide	repeats of two bp sequences
Tetranucleotide	repeats of four bp sequences
Microsatellite; Short Tandem Repeats (STRs)	short sequences of 100-200 bp, usually due to repeats of 1-6 bp sequences
Minisatellite	short sequences of 6-10 bp repeats
VNTR: Variable Number of Tandem Repeat	short nucleotide sequence ranging from 14 to 100 nucleotides long, organized into clusters of tandem repeats, usually repeated in the range of between 4 and 40 times per loci

Autosomes and Sex Chromosomes

There are 44 autosomes and 2 sex chromosomes in the human genome, for a total of 46 chromosomes (23 pairs). **Sex chromosomes** specify an organism's genetic sex. Humans can have two different sex chromosomes, one called X and the other Y. Normal females possess two X chromosomes and normal males one X and one Y. An **autosome** is any chromosome other than a sex chromosome. **Figure 3** 9.3 shows a representation of the 24 different human chromosomes. **Figure** 9.4 shows a karyotype of the human genome. A **karyotype** depicts, usually in a photograph, the chromosomal complement of an individual, including the number of chromosomes and any large chromosomal abnormalities. Karyotypes use chromosomes from the metaphase stage of mitosis.

The 22 autosomes are numbered based on size, with the largest chromosome labeled chromosome 1. These 22 chromosomes occur in homologous pairs in a normal diploid cell, with one of each pair inherited from each parent. The sex of an individual is determined by the sex chromosome within the male gamete. Females are homologous, XX, for the sex chromosomes, whereas males are heterozygous, XY. As all individuals inherit an X chromosome from their mother (females can only produce gametes with an X chromosome), it is the sex chromosome that they inherit from their father that determines their sex.

Both autosomal-linked and sex-linked traits and disorders will be discussed later in this chapter.

Sex-Linked Genes

Sex-linked genes are located on either the X or Y chromosome, though it more commonly refers to genes located on the X-chromosome. For that reason, the genetics of **sex-linked** (or **X-linked**) diseases, disorders due to mutations in genes on the X-chromosome, results in a phenotype usually only seen in males. This will be discussed in the next lesson.

In humans, the Y chromosome spans 58 million bases and contains about 78 to 86 genes, which code for only 23 distinct proteins, making the Y chromosome one of the smallest chromosomes. The X chromosome, on the other hand, spans more than 153 million bases and represents about 5% of the total DNA in women's cells, 2.5% in men's cells. The X chromosome contains about 2,000 genes, however few, if any, have anything to do with sex determination. The Y chromosome is the sex-determining chromosome in humans and most other mammals. In mammals, it contains the gene **SRY** (sex-determining region Y), which encodes the testes-determining factor and triggers testis development, thus determining sex. It is the presence or absence of the Y chromosome that determines sex.

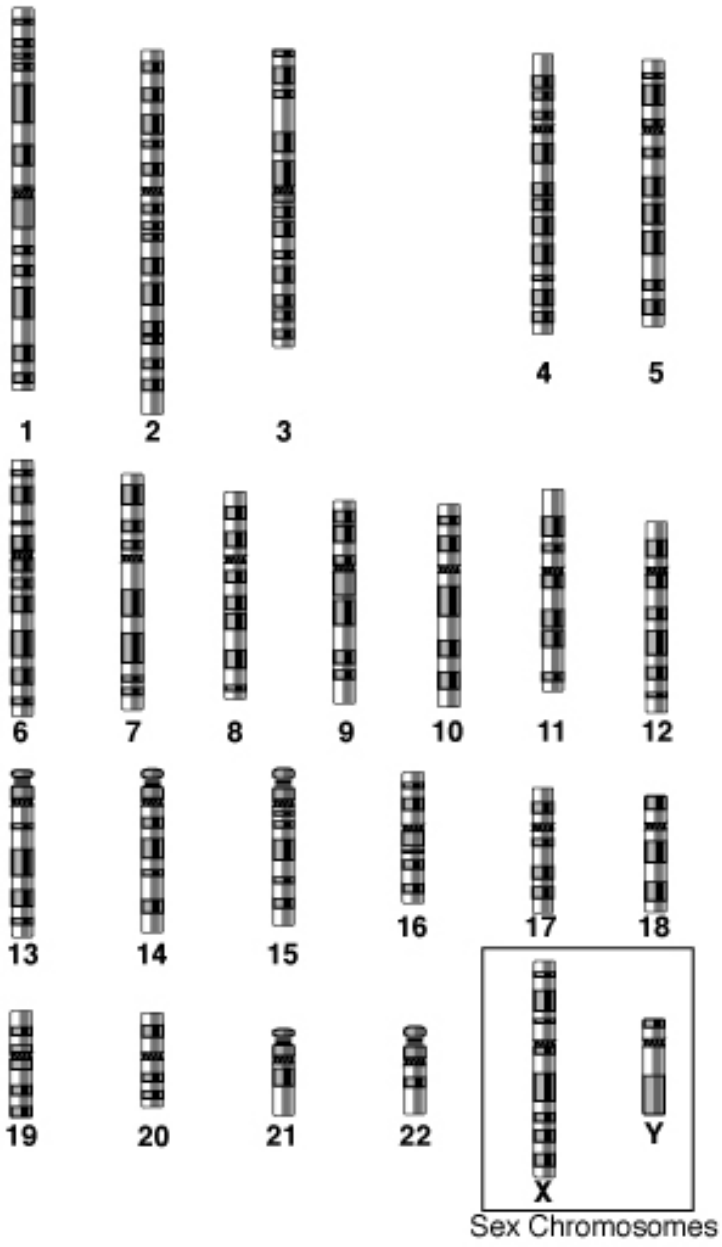

Figure 9.3: The 24 human chromosomes. The autosomes are numbered 1 - 22, based on size, with chromosome 1 being the largest. The X and Y sex chromosomes are shown in the box.

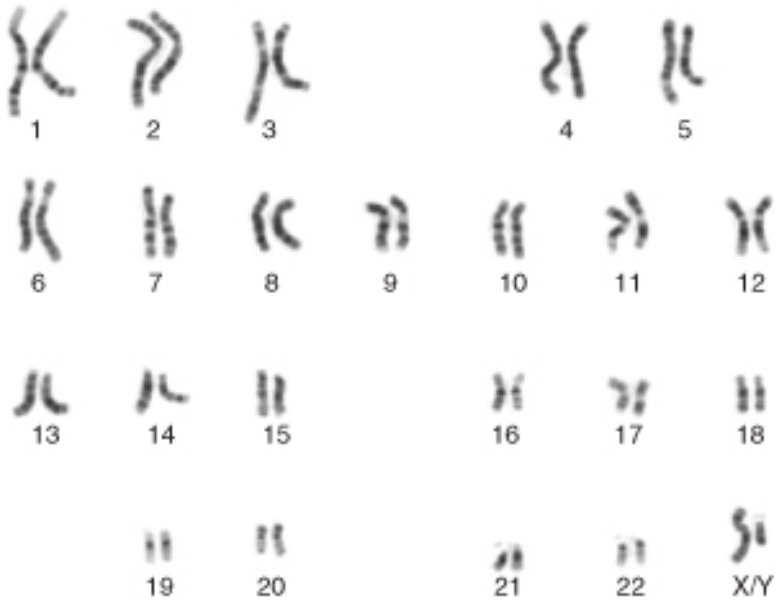

Figure 9.4: A karyotype of the human genome. Is this from a male or female?

X-Inactivation

Early in embryonic development in females, one of the two X chromosomes is randomly inactivated in nearly all somatic cells. This process, called **X-inactivation**, ensures that females, like males, have only one functional copy of the X chromosome in each cell. X-inactivation creates a Barr body, named after their discover, Murray Barr. The Barr body chromosome is generally considered to be inactive, however there are a small number of genes that remain active and are expressed.

Lesson Summary

- A genetic disease is a phenotype due to a mutation in a gene or chromosome.
- Many of these mutations are present at conception, and are therefore in every cell of the body.
- Mutant alleles may be inherited from one of both parents, resulting in a dominant or recessive hereditary disease.
- Currently there are over 4,000 known genetic disorders, with many more phenotypes yet identified.
- The genome refers to all the DNA of a particular species.
- The human genome consists of 24 distinct chromosomes: 22 autosomal chromosomes, plus the sex-determining X and Y chromosomes.
- Linkage refers to particular genetic loci or alleles inherited together, suggesting that they are physically on the same chromosome, and located close together on that chro-

mosome.
- The variation within the human genome results in the uniqueness of our species.
- There are 44 autosomes and 2 sex chromosomes in the human genome, for a total of 46 chromosomes.
- Sex chromosomes specify an organism's genetic sex. Humans have two different sex chromosomes, one called X and the other Y.
- Sex-linked genes are located on either the X or Y chromosome, though it more commonly refers to genes located on the X-chromosome.
- Early in embryonic development in females, one of the two X chromosomes is randomly inactivated in nearly all somatic cells. This process is called X-inactivation.

Review Questions

1. What is a genetic disease?
2. Discuss the main difference between autosomal and sex-linked.
3. Why is variation within the human genome important?
4. Why is it more common for males to have X-linked disorders?
5. Describe how a mutation can lead to a genetic disease.
6. Discuss how a new mutation can become a new dominant allele.
7. How are autosomal traits usually inherited? Give examples of traits.
8. How are genetic diseases usually inherited? Are there exceptions? Research examples.

Further Reading / Supplemental Links

- The National Human Genome research Institute:
- http://www.genome.gov
- The Dolan DNA Learning Center:
- http://www.dnalc.org/home_alternate.html
- DNA Interactive:
- http://www.dnai.org/
- A Science Odyssey: DNA Workshop:
- http://www.pbs.org/wgbh/aso/tryit/dna/
- Kimball's Biology Pages:
- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages
- http://en.wikipedia.org

Vocabulary

autosome Any chromosome other than a sex chromosome.

Barr body The inactive X-chromosome in females.

chromosome A threadlike molecule of genes and other DNA wound around histone proteins; located in the nucleus of a cell.

genetic counselor An individual trained in human genetics and counseling.

genetic disease A phenotype due to a mutation in a gene or chromosome.

geneticist A medical doctor specializing in genetic disorders.

genetics The branch of biology that focuses on heredity.

genome All of the hereditary information encoded in the DNA, including the genes and non-coding sequences.

karyotype Depicts, usually in a photograph, the chromosomal complement of an individual, including the number of chromosomes and any large chromosomal abnormalities.

linkage Refers to particular genetic loci or alleles inherited together, suggesting that they are physically on the same chromosome, and located close together on that chromosome.

microsatellite Short sequences of 100-200 bp, usually due to repeats of 1-6 bp sequences; also known as a STR (Short Tandem Repeat) polymorphism.

minisatellite Short sequence polymorphisms of 6-10 bp repeats.

proteome The complete set of proteins expressed by a genome, cell, tissue, or organism.

repetitive sequences DNA sequences that repeat a number of times; also known as repetitive elements.

sex chromosomes Specify an organism's genetic sex; in humans, the X and Y chromosomes.

sex-linked disease A disorder due to a mutation in a gene on the X-chromosome; also called X-linked disorder.

SNPs Single Nucleotide Polymorphisms; substitutions in individual bases along a gene or chromosome.

SRY Sex-determining region Y; gene which encodes the testes-determining factor and triggers testis development, thus determining sex; located on the Y chromosome.

VNTR Variable Number of Tandem Repeat; short nucleotide sequence ranging from 14 to 100 nucleotides long, organized into clusters of tandem repeats, usually repeated in the range between 4 and 40 times per loci.

X-inactivation The random inactivation of one X-chromosome in females; occurs early in embryonic development.

Points to Consider

- How are traits inherited? How about the inheritance of genetic disorders? Are inheritance patterns of traits and disorders similar?
- Could simple Mendelian inheritance account for such complex traits with vast phenotypic variation such as height or skin color? What do you think?

9.2 Lesson 9.2: Human Inheritance

Lesson Objectives

- Describe the difference between a genetic trait and a genetic disease/disorder.
- Define the various modes of inheritance, focusing on the differences between autosomal and sex-linked.
- Gives examples of dominant and recessive genetic disorders.
- Discuss the inheritance of sex-linked traits.
- Discuss complex inheritance patterns.
- Define codominant alleles and give examples.
- Define incomplete dominance.
- Give examples of multiple allele traits.
- Discuss how a trisomy condition may be detected.
- What is Down syndrome?
- List some examples of phenotypes due to abnormal numbers of sex chromosomes.
- Discuss the importance of gene therapy.
- Describe the most common method of gene therapy.

Introduction

What is a genetic trait? Is a genetic disease a trait? The answer to these questions may be debated, but a genetic trait is a characteristic of you encoded in your DNA. Could you say that a genetic disease is encoded in your DNA? Well, by definition, yes you can.

How are traits inherited? Do different traits have different patterns of inheritance? Is it as simple as a one allele – one phenotype relationship? Or is it more complex? Is there a difference if the gene is located on an autosome or a sex chromosome? Can there be traits due to multiple genes? The answer to all of the above questions is a resounding 'sometimes.' Sometimes it is as simple as a one allele – one phenotype relationship, sometimes it is more complex. Sometimes there is a difference depending on the location of the gene. Sometimes traits can be due to multiple genes. Human genetics is an exciting aspect of biology and medicine; an aspect of biology that is extremely important to our health and well being.

Autosomal and Sex-Linked Traits: Mutations and Genetic Disorders

Autosomal vs. sex-linked. In terms of genetics, is the location of a gene or trait an important piece of information? Does it make a difference if the gene is located on a sex chromosome or an autosome? It might. Remember from lesson 9.1 that sex chromosomes determine an organism's sex, so the autosomes are the other chromosomes. Autosomal-linked traits are due to genes on the **autosomes**; **sex-linked traits** are due to genes located on the **sex chromosomes**.

What is the difference between a trait and a genetic disorder? Could a disorder be considered a trait? We tend to think of traits as hair color or skin color and disorders as something that is bad for you. But in terms of genetics, a genetic disorder is a trait. Both may be due to your genes.

Simple Dominant Heredity

How are traits due to genes on autosomes inherited? Autosomal traits due to the effects of one gene are usually inherited in a simple Mendelian pattern. That is, they can be either dominant or recessive. In humans, whereas many genetic disorders are inherited in a recessive manner, simple dominant inheritance accounts for many of a person's physical characteristics, such as chin, earlobe, hairline and thumb shape. For example, having earlobes that are attached to the head is a recessive trait, whereas heterozygous and homozygous dominant individuals have freely hanging earlobes. If you have a cleft chin, a pointed frontal hairline (called a widow's peak), or a hitchhiker's thumb, you have inherited the dominant allele for each characteristic from at least one of your parents. Other dominant traits include the presence of hair on the middle section of your fingers, thick lips, and almond-shaped eyes. A widow's peak and earlobe shape are displayed in **Figure** 9.5 and **Figure** 9.6.

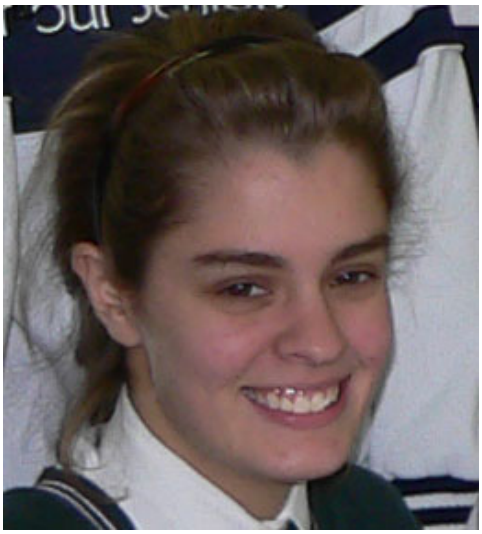

Figure 9.5: A young woman with a widow's peak, due to a dominant allele.

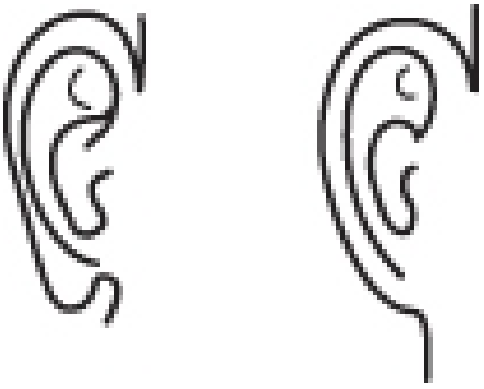

Figure 9.6: A diagram showing free (left) and attached (right) earlobes. Attached earlobes is a recessive trait.

Mutations and Genetic Disorders

Mutations, changes in the DNA or RNA sequence, can have significant phenotypic effects or no effects. We have previously discussed various types of mutations. Now, let's discuss the outcomes of some of those mutations. As mentioned at the beginning of this chapter, a genetic disorder is a condition caused by abnormalities, such as mutations, in your genes or chromosomes. Genetic disorders are usually present from conception. These disorders include chromosomal abnormalities, in which the individual has too few or too many chromosomes or chromosomes with large alterations, or diseases due to a mutation in a specific gene. These defective genes are usually inherited from the parents, hence the term hereditary disease or genetic disorder. Genetic disorders can be inherited in a dominant or recessive manner (**Figure** 9.7 and **Figure** 9.8). Recessive disorders require the inheritance of a defective gene from each parent. The parents are usually unaffected and are healthy carriers of the defective gene.

How can you, or a geneticist, determine the inheritance pattern of a phenotype? A **pedigree**, which is essentially a representation of genetic inheritance, is helpful. A pedigree is a chart, much like a family tree, which shows all of the known individuals within a family with a particular phenotype (**Table** 9.2). Pedigrees have been discussed in the chapter titled *Mendelian Genetics*. Examples of autosomally inherited disorders include cystic fibrosis, Tay-Sachs disease, phenylketonuria, and achondroplasia.

Table 9.2: **Autosomal and Sex-linked Inheritance Patterns**

Inheritance Pattern	Description	Example
Autosomal Dominant	Only one mutated allele is needed for a person to be affected by an **autosomal dominant disorder**. Each affected person usually has one affected parent. There is a 50% chance that a child will inherit the mutated gene.	Huntingtons disease, Achondroplasia, Neurofibromatosis 1, Marfan Syndrome, Hereditary nonpolyposis colorectal cancer
Autosomal Recessive	Both copies of the gene must be mutated for a person to be affected by an **autosomal recessive disorder**. An affected person usually has unaffected parents who each carry a single copy of the mutated gene (and are referred to as carriers).	Cystic fibrosis, Sickle cell anemia, Tay-Sachs disease, Spinal muscular atrophy

Table 9.2: (continued)

Inheritance Pattern	Description	Example
X-linked Dominant	**X-linked dominant disorders** are caused by mutations in genes on the X chromosome. Only a few disorders have this inheritance pattern.	
X-linked Recessive	**X-linked recessive disorders** are also caused by mutations in genes on the X chromosome. Males are more frequently affected than females. The sons of a man with an X-linked recessive disorder will not be affected, and his daughters will carry one copy of the mutated gene. A woman who carries an X-linked recessive disorder has a 50% chance of having sons who are affected and a 50% chance of having daughters who carry one copy of the mutated gene.	Hemophilia A, Duchenne muscular dystrophy, Color blindness
Y-Linked	**Y-linked disorders** are caused by mutations on the Y chromosome. Only males can get them, and all of the sons of an affected father are affected. Y-linked disorders only cause infertility, and may be circumvented with the help of some fertility treatments.	Male Infertility

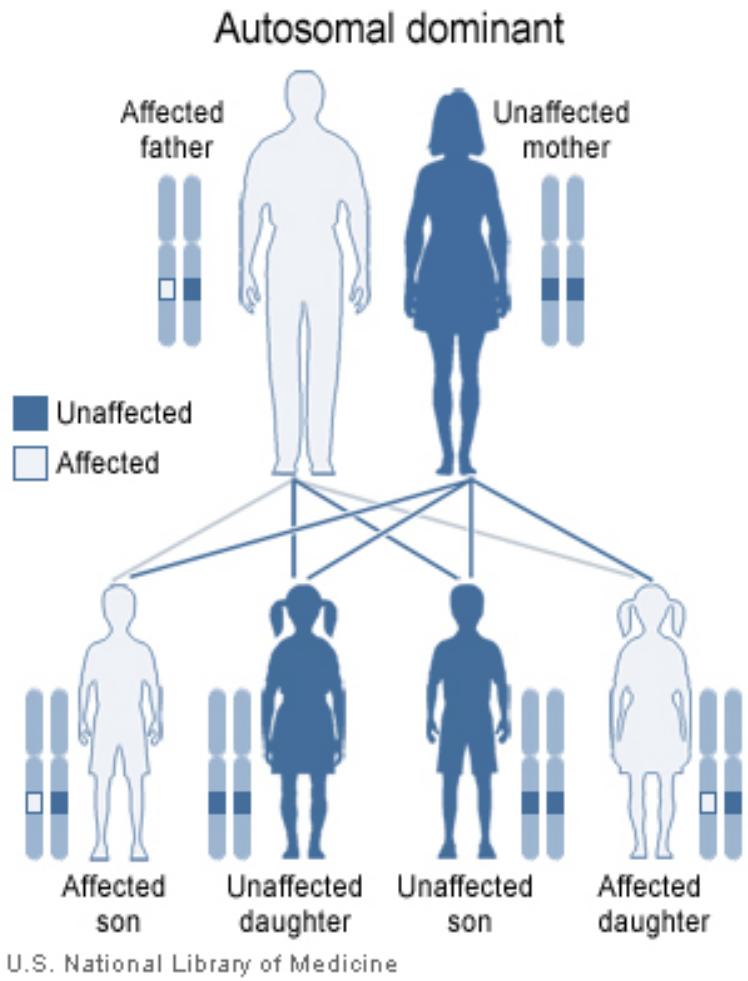

Figure 9.7: Autosomal Dominant Inheritance. Only one "affected" allele is necessary to result in the "affected" phenotype. For a genetic disease inherited in this manner, only one mutant allele is necessary to result in the phenotype. Achondroplasia (discussed later) is an example of a dominant disorder. Both homozygous and heterozygous individuals will show the phenotype.

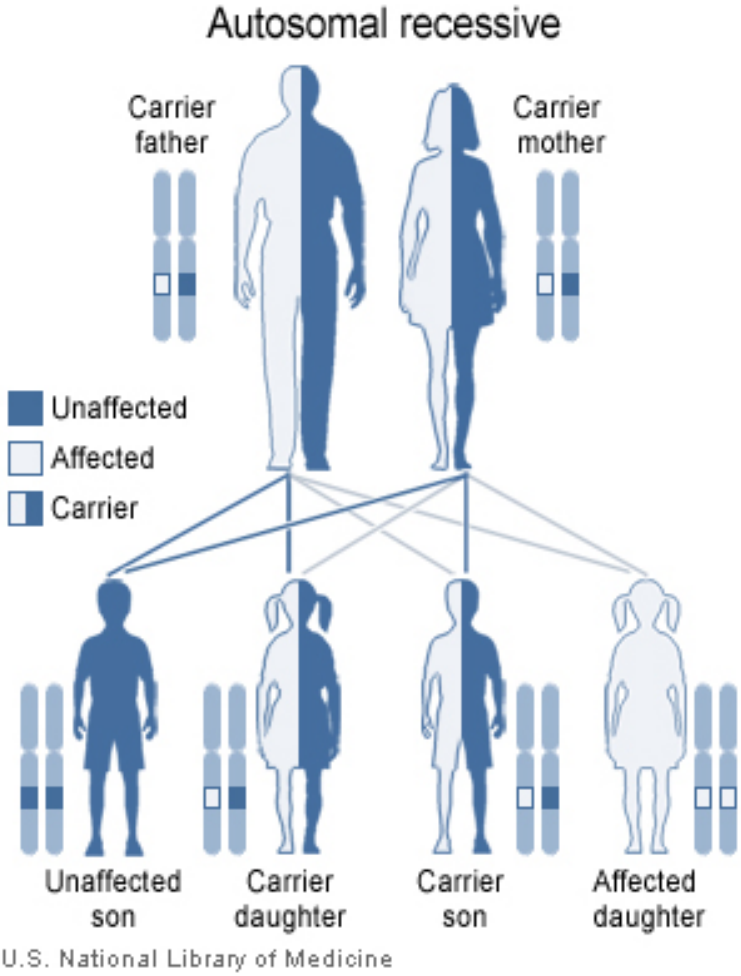

Figure 9.8: Autosomal Recessive inheritance. For a genetic disease inherited in this manner, two mutant alleles are necessary to result in the phenotype. Tay-Sachs Disease (discussed later) is an example of a recessive disorder. Notice that both parents are unaffected carriers of the mutant allele. These unaffected carriers allow the allele to be maintained in the gene pool - the complete set of a population's genes. Even if the allele is lethal in the homozygous recessive condition, the allele will be maintained through heterozygous individuals.

Cystic Fibrosis

Cystic fibrosis (CF) is a recessive inheritable disorder caused by a mutation in a gene called the cystic fibrosis transmembrane conductance regulator (CFTR). The product of this gene is a chloride ion channel important in creating sweat, digestive juices, and mucus. Although most people without CF have two working copies of the CFTR gene, only one is needed to prevent cystic fibrosis. CF develops when individuals have a mutation in both copies of the gene, such that neither gene product works normally. CF is one of the most common life shortening diseases. Diagnosis is usually made in childhood. In the United States, approximately 1 in 3,900 children is born with CF (**Figure** 9.9). One in 22 people of European descent are carriers of a mutated CFTR gene. CF mainly affects the lungs and digestive system, causing difficulty breathing due to thick mucus production, progressive disability, and for some individuals, premature death.

Individuals can be diagnosed prior to birth by genetic testing. Because development of CF in the fetus requires each parent to pass on a mutated copy of the CFTR gene and because CF testing is expensive, testing is often initially performed on just one parent. If that parent is found to be a carrier of a CFTR gene mutation, the other parent is then tested to calculate the risk that their children will have CF. CF can result from more than a thousand different mutations; currently it is not possible to test for each one. As new DNA testing methodologies are developed, testing for more mutations will become more common and less expensive. Testing analyzes DNA for the most common mutations, such as a deletion of amino acid 508 (phenylalenine, also known as ΔF508). If a family has a known uncommon mutation, specific screening for that mutation can be performed. However, it must be noted that because there may be other not yet identified mutations that result in CF, and as not all known mutations are found on current tests, a negative screen does not guarantee that a child will not have CF.

Tay-Scahs Disease

Tay-Sachs disease is a genetic disorder that is fatal in its most common variant, known as Infantile Tay-Sachs disease. Tay-Sachs is an autosomal recessive disorder, requiring the inheritance of a defective gene from each parent. The disease results from the accumulation of harmful quantities of fat in the nerve cells of the brain. Tay-Sachs results from mutations in the HEXA gene located on chromosome 15, which encodes the alpha-subunit of the lysosomal enzyme beta-N-acetylhexosaminidase A, which normally breaks down the fat. More than 90 mutations, including substitutions, insertions, deletions, splice site mutations, and other more complex patterns have been characterized in this gene, and new mutations are still being reported. Each of these mutations alters the protein product, inhibiting the function of the enzyme.

Tay-Sachs disease is a rare disease. Unaffected carriers of a Tay-Sachs allele may not know they have the allele. Other autosomal disorders such as cystic fibrosis and sickle cell anemia

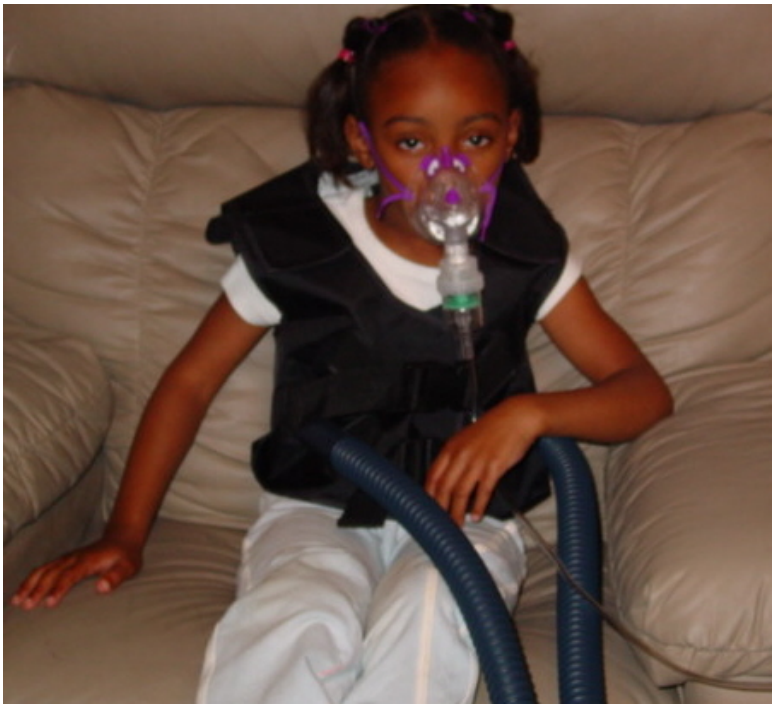

Figure 9.9: A young cystic fibrosis patient undergoing breathing treatment. Cystic fibrosis is a recessively inherited genetic disorder.

are far more common. The importance of Tay-Sachs lies in the fact that an inexpensive enzyme assay test was developed. The automation of this analysis has provided one of the first "mass screening" tools in medical genetics. Two unaffected carriers can have a child homozygous for a Tay-Sachs allele, resulting, currently, in a lethal phenotype. Tay-Sachs alleles are maintained in a population through these unknowing heterozygous carriers.

The analysis and screening for Tay-Sachs has became a research and public health model for understanding and preventing all autosomal genetic disorders. Another genetic disease that is easily analyzed in phenylketonuria.

Phenylketonuria

Phenylketonuria (PKU) is an autosomal recessive genetic disorder characterized the inability to metabolize the amino acid phenylalanine. PKU is due to a deficiency in the enzyme phenylalanine hydroxylase (PAH). When PAH is deficient, phenylalanine accumulates and is converted into phenylketones, which can be detected in the urine. Left untreated, this condition can cause problems with brain development, leading to progressive mental retardation and seizures. However, PKU can be treated with a specific diet, one low in phenylalanine. A diet low in phenylalanine and high in tyrosine can bring about a nearly total cure.

The incidence of PKU is about 1 in 15,000 live births. In the United States PKU is screened at birth as part of a national biochemical screening program, for every baby born in a hospital. Babies born at home may not be screened. If PKU is diagnosed early enough, an affected newborn can grow up with normal brain development, but only by eating a special diet low in phenylalanine for the rest of his or her life. In essence, this is a protein-free diet. This requires severely restricting or eliminating foods high in protein content (containing phenylalanine), such as breast milk, meat, chicken, fish, nuts, cheese and other dairy products. Starchy foods such as potatoes, bread, pasta, and corn must also be monitored. Many diet foods and diet soft drinks that contain the sweetener aspartame must also be avoided, as aspartame consists of two amino acids: phenylalanine and aspartic acid. Supplementary infant formulas are used in these patients to provide the amino acids and other necessary nutrients that would otherwise be lacking in their diet. Since phenylalanine is required for the synthesis of many proteins, it is necessary to have some of this amino acid, but levels must be strictly controlled. In addition, tyrosine, which is normally derived from phenylalanine, must also be supplemented.

Achondroplasia

Whereas cystic fibrosis, Tay-Sachs, and phenylketonuria are all autosomal recessive disorders, **achondroplasia** is an autosomal dominant disorder. Achondroplasia is the most common cause of dwarfism. Achondroplasia is a result of an autosomal dominant mutation in the fibroblast growth factor receptor gene 3 (FGFR3), which causes an abnormality of cartilage formation. FGFR3 normally has a negative regulatory effect on bone growth. In achondroplasia, the mutated form of the receptor is constitutively active (constantly "turned on") and this leads to severely shortened bones. Individuals with achondroplasia are heterozygous for the mutation (one mutant copy, one normal copy). Homozygous for the achondroplasia mutation is lethal prior to birth or shortly after birth.

For autosomal dominant disorders, a person with the disorder has a 50% chance of passing on the gene to their offspring. For achondroplasia, this means there will be a 50% chance that each child will have achondroplasia. Since two copies are fatal, if two people with achondroplasia have a child, there is a 25% chance of the child dying shortly after birth, a 50% chance the child will have achondroplasia, and a 25% chance the child will have a normal phenotype. However, in 3 out of 4 cases, people with achondroplasia are born to parents who don't have the condition. This is the result of a new mutation. New achondroplasis mutations are associated with increasing paternal age (over 35 years). Studies have demonstrated that new gene mutations are exclusively inherited from the father and occur during spermatogenesis. More than 98% of achondroplasia is caused by a G to A point mutation at nucleotide 1138 of the FGFR3 gene, which causes a glycine to arginine substitution. This makes this particular nucleotide one of the most, if not the most, mutable base in the human genome.

There are three other syndromes with a genetic basis similar to achondroplasia: hypochon-

droplasia, thanatophoric dysplasia, and SADDAN Dysplasia (severe achondroplasia, developmental delay, acanthosis nigricans (a skin condition)). Each of these disorders is also caused by a mutation in the *FGFR3* gene. Each of the conditions results in a distinct difference in the degree of severity of the phenotype, with hypochondroplasia having the mildest phenotype. Other genes in which mutations cause a phenotypic spectrum of disease include the collagen genes among others.

Sex-Linked Traits

Traits controlled by genes located on the sex chromosomes (X and Y) are called sex-linked traits (**Figure** 9.10). Remember, females have two X chromosomes and males have a X and a Y chromosome. Therefore, any recessive allele on the X chromosome of a male will not be masked by a dominant allele. X-linked traits include the hemophilia and color blindness. Hemophilia is the name of a family of hereditary genetic illnesses that impair the body's ability to control coagulation. Color Blindness, or color vision deficiency, in humans is the inability to perceive differences between some or all colors that other people can distinguish.

Hemophilia is a group of diseases in which blood does not clot normally. Factors in blood are involved in clotting. Hemophiliacs lacking the normal Factor VIII are said to have Hemophilia A, the most common form. England's Queen Victoria was a carrier for this disease. The allele was passed to two of her daughters and one son. Since royal families in Europe commonly intermarried, the allele spread, and may have contributed to the downfall of the Russian monarchy.

Genetic red-green color blindness affects men much more often than women, because the genes for the red and green color receptors are located on the X chromosome. Females are red-green color blind only if both of their X chromosomes carry the defective gene, whereas males are color blind if their single X chromosome carries the defective gene. As males have only the one X-chromosome, the gene for red-green color blindness is transmitted from a color blind male to all his daughters, who are usually heterozygous carriers and therefore unaffected. Subsequently, this carrier woman has a fifty percent chance of passing on a X chromosome with a defective gene to each of her male offspring. The sons of an affected male will not inherit the trait from him, since they receive his Y chromosome and not his X chromosome. Should an affected male have children with a carrier or colorblind woman, their daughters may be colorblind by inheriting a X chromosome with the mutant gene from each parent.

Muscular dystrophy is a term encompassing a variety of muscle wasting diseases. The most common type, **Duchenne Muscular Dystrophy** (DMD), affects cardiac and skeletal muscle, as well as some mental functions. DMD is an X-linked recessive disorder occurring in 1 in 3,500 newborns. Most affected individuals die before their 20th birthday.

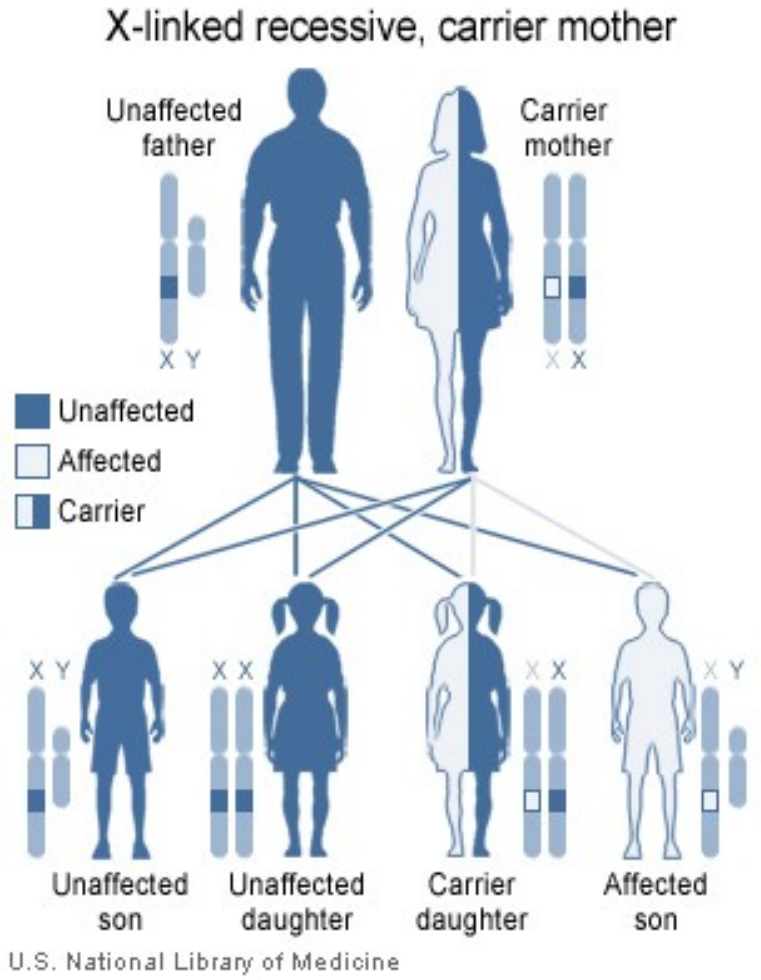

Figure 9.10: X-linked recessive inheritance. As boys have only one X-chromosome, if they inherit the mutant allele from their mother, they will possess the phenotype that results from that allele.

Complex Traits

So far we have discussed traits inherited in a simple Mendelian pattern. Either the trait is dominate or recessive. The trait is affected by only one gene. But this is not the case for many genes; rarely is inheritance that simple. More complex patterns of inheritance are common. These were introduced in the chapter titled *Mendelian Genetics*.

Mendel's pea plants showed complete dominance of one allele over the other. The offspring always completely looked like one of the parents – there was never any phenotype "in between" the two parents. The heterozygous individuals were indistinguishable from the homozygous dominant individuals. Is it possible for both alleles to be dominant, or neither to be completely dominant? The answer to both of these questions is yes.

Codominance

Codominance is when two alleles are both expressed in the heterozygous individual; that is, they both affect the phenotype in separate and distinguishable ways (**Figure** 9.11). The A, B alleles of the ABO blood group system are a classic example, and these have been discussed in the chapter titled *Mendelian Genetics.* The A and B alleles are codominant with each other. When a person has both an A and a B allele, the person has type AB blood. When two persons with AB blood type have children, the children can be type A, type B, or type AB. There is a 1A:2AB:1B phenotype ratio instead of the 3:1 phenotype ratio found when one allele is dominant and the other is recessive.

Incomplete Dominance

Incomplete dominance is seen in heterozygous individuals with an intermediate phenotype. For example, if Mendel had ever observed a medium stem length plant when a tall and short plant were crossed, that would have suggested incomplete dominance. In incomplete dominant situations, the phenotype expression is dependent on the dosage of the genes. Two copies of the gene result in full expression, while only one copy produces partial expression and an intermediate phenotype.

Multiple-Allele Traits

Traits controlled by more than two alleles have multiple alleles. Theoretically, any base change will result in a new allele. In fact, within the human population, it may be safe to say that most human genes have more than 2 alleles. Whereas, we think of base changes, or mutations, as resulting in a new phenotype or disease, many base changes result in alleles that do not cause significant change in phenotypes. This is common in collagen genes, for example. The best characterized example of multiple alleles in humans is the ABO blood

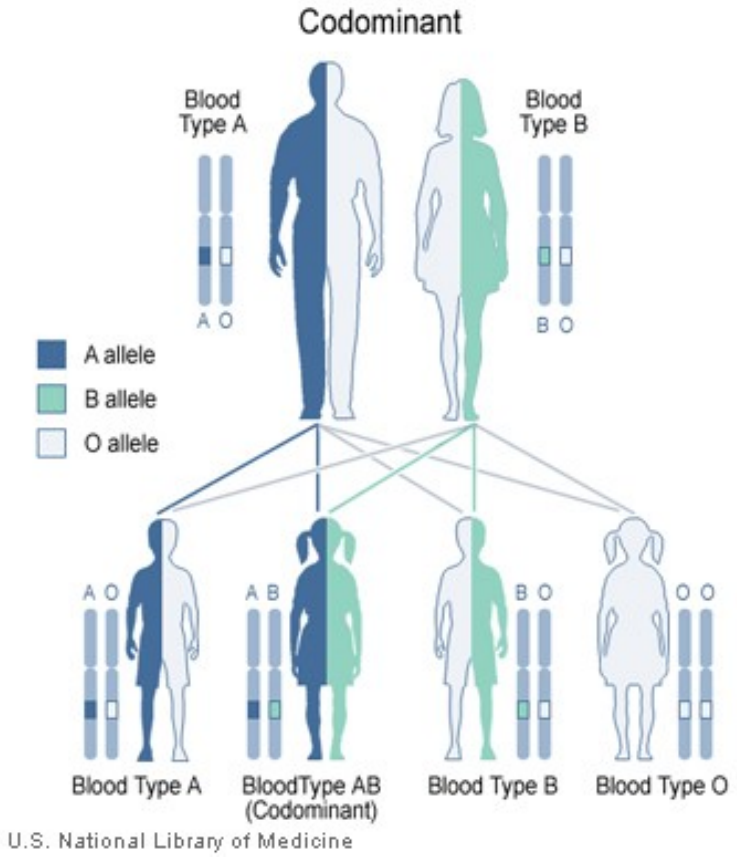

Figure 9.11: Codominant Inheritance. The A and B alleles are codominant. An AB heterozygous individual has type AB blood.

groups, discussed in the chapter titled *Mendelian Genetics*.

It is easiest to consider situations where each gene affects only one phenotypic characteristic. However, other situations where genes have other effects are common. As mentioned above, multiple alleles resulting in multiple phenotypes are not uncommon.

Pleiotropy

Many genes have multiple phenotypic effects, a property called **pleiotropy**. Thus, a new mutation in the gene will affect all the phenotypes/traits associated with the gene simultaneously. For example, the symptoms associated with sickle-cell disease are due to pleiotropic alleles. Another example is the collagen genes mentioned above. As you will learn later, many bones develop from a cartilage template. This cartilage template is made out of many proteins, with type II collagen, the predominant protein in the cartilage. The gene for this collagen, COL2A1, when mutated, not only affects the skeletal system, but due to its pleiotropic nature, it may also affect a person's eyes and hearing.

Epistasis

Epistasis is when a gene at one location (locus) alters the phenotypic expression of a gene at another locus. This is seen in the inheritance of coat color in mice. Epistasis takes place when the action of one gene is modified by one or several other genes, which are sometimes called modifier genes. The gene whose phenotype is expressed is said to be epistatic, while the phenotype altered or suppressed is said to be hypostatic.

Polygenic Traits

Polygenic traits are due to the actions of more than one gene and often, their interaction with the environment. These usually result in a measurable range in phenotype, such as height, eye color or skin color. These are known as multifactoral or quantitative characteristics. Polygenic inheritance results in an additive effect of the genes on a single phenotype.

Skin color is a polygenic trait and obviously demonstrates quantitative characteristics. A number of genes factor into determining a person's natural skin color, so modifying only one of those genes changes the color only slightly. It is currently thought that at least three separately inherited genes contribute to skin pigmentation. Let's call these three genes A, B, and C. A, B, and C are incompletely dominant to a, b, and c, with A, B, and C each contributing a "unit of darkness" to the phenotype. Therefore an AABBCC individual is very dark, darker than an AaBbCc individual, and much darker than a aabbcc individual. A person may have as many as 6 "dark units" to as few as no "dark units," and any combination in between. This will result in a phenotypic spectrum of color gradation.

Many disorders with genetic components are polygenic, including autism, certain cancers, diabetes and numerous others. Most phenotypic characteristics are the result of the interaction of multiple genes. The environment plays a significant role in many of these phenotypes. But what happens when multiple genes are either missing or duplicated?

Changes in Chromosome Number

So far we have focused on traits due to one gene or several genes. But what about many genes? What would happen if an entire chromosome were missing or duplicated? What if a human had only 45 chromosomes? Or 47? This real possibility is usually due to mistakes during meiosis; the chromosomes do not fully separate from each other during sperm or egg formation. Specifically, **nondisjunction** is the failure of replicated chromosomes to separate during anaphase II. If a zygote forms from a gamete lacking a chromosome, a viable embryo cannot be produced. Most human abnormal chromosome numbers result in the death of the developing embryo, often before a woman even realizes she is pregnant. Occasionally, a zygote with an extra chromosome can become a viable embryo and develop.

Trisomy is a state where humans have an extra autosome. That is, they have three of a particular chromosome instead of two. For example, trisomy 18 results from an extra chromosome 18, resulting in 47 total chromosomes. To identify the chromosome number (including an abnormal number), a sample of cells is removed from an individual or developing fetus. Metaphase chromosomes are photographed and a karyotype is produced. A karyotype will display any abnormalities in chromosome number or large chromosomal rearrangements. Trisomy 8, 9, 12, 13, 16, 18, and 21 have been identified in humans. Trisomy 16 is the most common trisomy in humans, occurring in more than 1% of pregnancies. This condition, however, usually results in spontaneous miscarriage in the first trimester. The most common trisomy in viable births is **Trisomy 21**.

Trisomy 21: Down Syndrome

One of the most common chromosome abnormalities is Down syndrome, due to nondisjunction of chromosome 21 resulting in an extra complete chromosome 21, or part of chromosome 21 (**Figure** 9.13). Down syndrome is the only autosomal trisomy where an affected individual may survive to adulthood. Individuals with Down syndrome often have some degree of mental retardation, some impairment of physical growth, and a specific facial appearance. With proper assistance, individuals with Down syndrome can become successful, contributing members of society (**Figure** 9.14). The incidence of Down syndrome increases with maternal age.

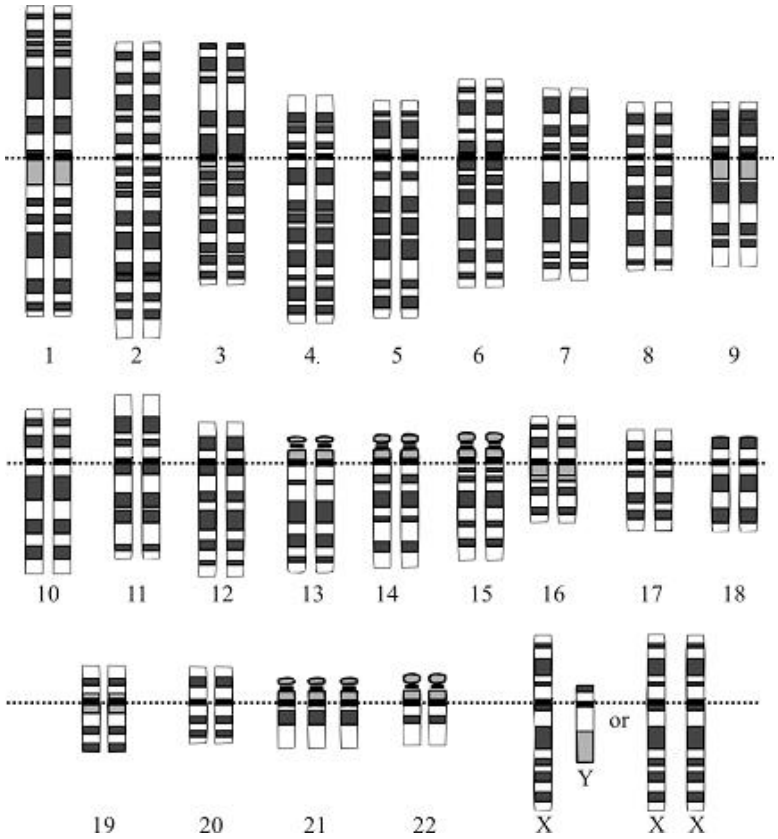

Figure 9.12: Trisomy 21 (Down Syndrome) Karyotype. Note the extra chromosome 21.

Figure 9.13: Child with Down syndrome, exhibiting characteristic facial appearance.

Figure 9.14: Boy with Down Syndrome assembling a bookcase.

Abnormal Numbers of Sex Chromosomes

What about when a person has more than 2 Y chromosomes, or more than 2 X chromosomes? Or a female with only one X chromosome? Sex-chromosome abnormalities may be caused by nondisjunction of one or more sex chromosomes. Many conditions are known in which there are an abnormal number of sex chromosomes. An X chromosome may be missing (XO), or there may be an extra one (XXX or XXY). There may also be an extra Y chromosome (XYY). Any combination of X and Y chromosomes, as long as there is a Y chromosome, will produce a male (up to XXXXY). These individuals can lead relatively normal lives, but they cannot have children. They may also have some degree of mental retardation. These syndromes include Klinefelter's syndrome, Turner syndrome and trisomy X.

Klinefelter's syndrome is caused by the presence of one or more extra copies of the X chromosome in a male's cells. Extra genetic material from the X chromosome interferes with male sexual development, preventing the testicles from functioning normally and reducing the levels of testosterone. Triple X syndrome (**trisomy X**) results from an extra copy of the X chromosome in each of a female's cells. Females with trisomy X have a lower IQ than their siblings. Turner syndrome results when each of a female's cells has one normal X chromosome and the other sex chromosome is missing or altered. The missing genetic material affects development and causes the characteristic features of the condition, including short stature and infertility.

Diagnosis and Treatment of Genetic Disorders

If someone has a rare genetic disease in her family, can she still have a baby? Is she predisposed to pass that phenotype along to her child? These are questions for a professional trained in human genetics. A geneticist and **genetic counselor** are usually involved in the diagnosis and treatment of human genetic disorders. Families with a genetic disease are referred to a genetic counselor, especially when they wish to determine a baby's likelihood of inheriting a genetic disease.

Individuals or their families at risk of inheriting a genetic disorder have many questions. What exactly is a genetic disorder? How does a person get it? Can it be passed onto the next generation? Can it be treated? What are the symptoms? Do the symptoms get worse with age? These and many more questions are where a genetic specialist, such as a genetic counselor can help. **Genetic counseling** is the process by which individuals or their families who are at risk of an inherited disorder, are counseled on many different aspects of the disorder. Genetic counseling may be necessary at any time throughout life, from before pregnancy to adulthood. Before pregnancy, genetic counseling would be appropriate for at risk individuals who are planning a family, such as when one or both individuals are either carriers or have a certain genetic trait. During pregnancy, genetic counseling is necessary for couples if the woman will be over 35 years of age at the time of delivery, if prenatal testing is recommended for any reason, or if an abnormality is noted on an ultrasound or other test. After birth, genetic counseling is appropriate if a birth defect is detected. During childhood, genetic counseling is appropriate if the child manifests any signs of developmental delay or a genetic syndrome, and in adulthood, genetic counseling is appropriate if signs of an adult onset genetic disorder is detected. During genetic counseling, individuals are advised of the consequences and nature of the disorder, the probability of developing or transmitting the disorder, and the options open to them in management and family planning in order to make appropriate decisions. In terms of the actual diagnosis of the disease, molecular analysis may be necessary; this will be discussed in the chapter titled Biotechnology.

Prenatal Diagnosis

"Is it possible to test the developing baby for potential genetic problems? Do you need to remove some of the baby's DNA? How do you do that?" These questions are appropriate for a geneticist. Sometimes, to make sure the baby is developing properly, prenatal diagnosis is necessary. **Prenatal diagnosis** refers to the diagnosis of a disease or condition before the baby is born. The reason for prenatal diagnosis is to detect birth defects such as neural tube defects, chromosome abnormalities, genetic diseases and other conditions. It can also be used to determine the sex of the unborn baby, though this can usually be determined by an ultrasonography (ultrasound).

Diagnostic prenatal testing can be by invasive methods or non-invasive methods. Non-invasive methods are much less risky to the patient. Non-invasive methods can only evaluate

the risk of a condition and cannot actually determine if the fetus has a condition. Non-invasive techniques include examinations of the mother's womb through ultrasonography and analysis of maternal serum. If an abnormality is indicated by a non-invasive procedure, a more invasive technique may be employed to gather more information. **Amniocentesis** and **chorionic villus sampling** (CVS) are invasive procedures. These involve probes or needles that are inserted into the placenta. Amniocentesis can be done from about 14 weeks up to about 20 weeks of the pregnancy and CVS can be done earlier, between 9.5 and 12.5 weeks, but is slightly more risky to the unborn child.

During Amniocentesis a small amount of amniotic fluid, which contains fetal tissues, is extracted from the amnion or amniotic sac surrounding a developing fetus, and the fetal DNA is examined for genetic abnormalities. Amniocentesis is not performed for every pregnancy, but is generally done when an increased risk of genetic defects in the fetus is indicated, by mother's age (over 35 years is common), family history of genetic defects, or other factors.

Chorionic villus sampling (CVS) involves removing a sample of the chorionic villus (placental tissue) and testing it. It is generally carried out only on pregnant women over the age of 35 and those whose offspring have a higher risk of Down syndrome and other chromosomal conditions. The advantage of CVS is that it can be carried out 10-12 weeks after the last period, earlier than amniocentesis.

DNA from the developing baby may be isolated from either an amniocentesis or CVS. A karyotype may be created from fetal chromosomes following either procedure, or a specific mutation may be analyzed. The analysis of specific mutations will be discussed in the chapter titled Biotechnology.

Gene Therapy

So, how do you treat genetic disorders? If medically possible, each manifestation can be treated separately. But is there a way to use genetics to treat the root cause of the disease – that is, to fix the mistake in the DNA?

Gene therapy is the insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele. Although the technology is still in its early stages of development, it has been used with some success.

There are a number of mechanisms used to replace or repair a defective gene in gene therapy.

- A normal gene may be inserted into a nonspecific location within the genome to replace a nonfunctional gene. This approach is most common.
- An abnormal gene could be replaced by a normal gene through homologous recombination.
- The abnormal gene could be repaired through selective reverse mutation, which returns the gene to its normal, non-mutant state.

- The regulation (the degree to which a gene is turned on or off) of a particular gene could be altered.

As stated above, the most common gene therapy approach is to replace a disease-causing allele with a normal allele. To deliver the new allele to the appropriate cells, a carrier, called a vector, must be used. Currently, the most common type of vectors are viruses that have been genetically altered to carry normal human DNA, and not to result in any phenotypes associated with the virus. As viruses have evolved a robust method of delivering their viral genes to human cells, scientists have tried to develop (and are continuing to develop) methods to take advantage of this process, and have these vectors insert human DNA into target cells. Scientists have manipulated the viral genome to remove disease-causing genes and insert therapeutic human genes (**Figure** 9.15). For obvious reasons, this is currently a field of intense biomedical research.

A patient's target cells, such as liver or lung cells are infected with the genetically altered virus. The vector then unloads its genetic material containing the therapeutic human gene into the target cell. The generation of a functional protein product from the therapeutic gene should restore the target cell to a normally functioning phenotype. To date, this process has had limited success, but who can say what will happen in the future.

Severe Combined Immunodeficiency

Severe Combined Immunodeficiency, or SCID, is a heritable immunodeficiency - a genetic disorder that cripples the immune system. It is also known as the 'bubble boy' disease, named after David Vetter, SCID's most famous patient who lived for over 12 years in a sterilized environment, just like living inside a "bubble." SCID affects about 1 in 100,000 live births. These babies, if untreated, usually die within one year due to severe, recurrent infections. Treatment options have improved considerably and include bone marrow transplants and gene therapy. Children no longer have to live inside a bubble as did David Vetter, who was placed inside his sterile bubble about 10 seconds after birth. He died 15 days after he left his sterile environment, due to an undetected virus in the bone marrow transplant. David was one of the first bone marrow recipients.

More recently gene therapy has proved successful in treating SCID. Insertion of the correct gene into cells of the immune system should correct the problem. Trials started in 1990, and in 1999, the first SCID patients were detected with functional immune systems. Due to some complications these trials had to be stopped, but these issues seem to have been resolved. Gene therapy in individuals with SCID have been human genetics only gene therapy success stories. Since 1999, gene therapy has restored the immune systems of at least seventeen children with the disorder. This raises great hope for other genetic disorders. In your lifetime, it is definitely possible that many genetic disorders may be "cured" by gene therapy. As was mentioned earlier, no one can say what will happen in the future, and no one knows what lies ahead.

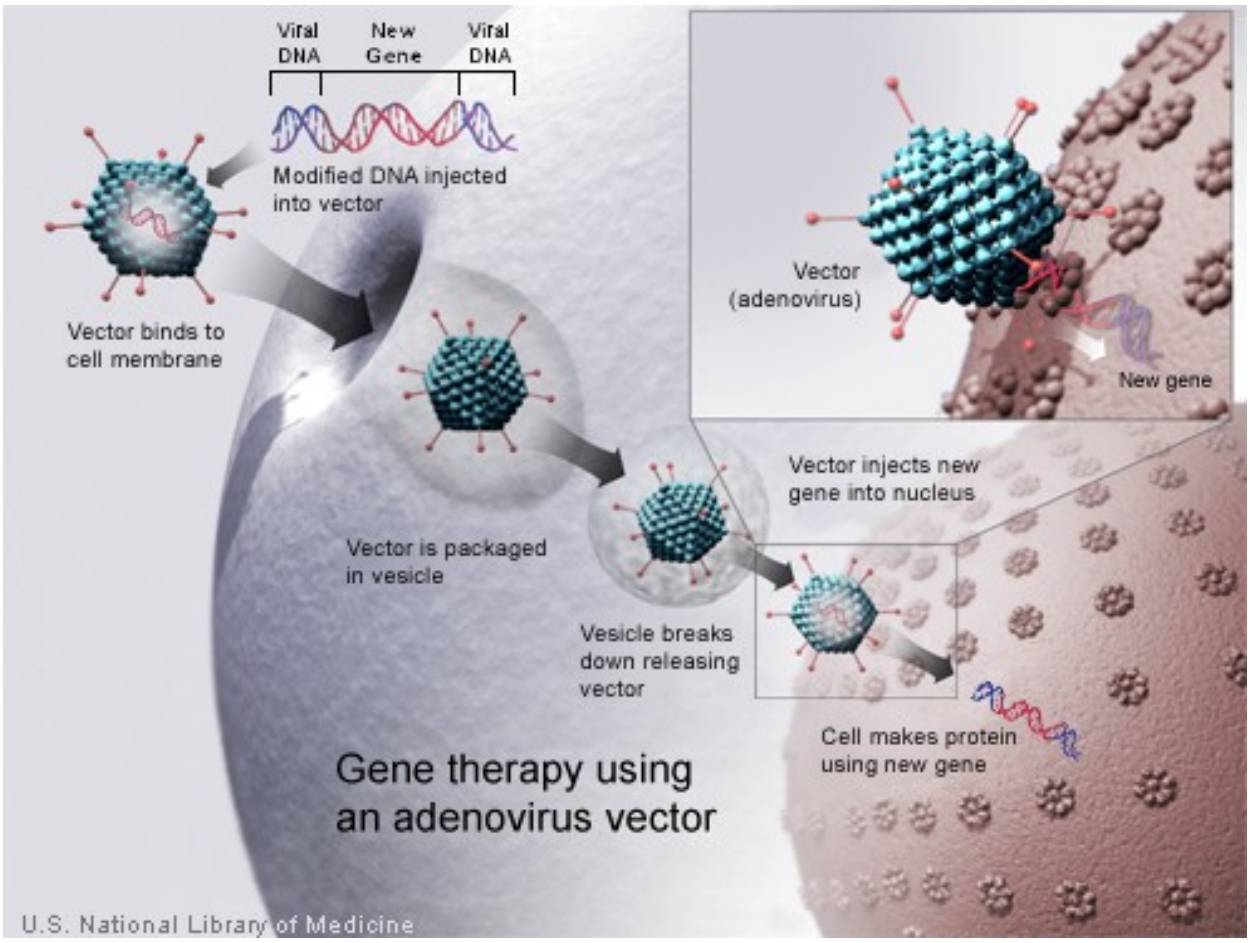

Figure 9.15: Gene Therapy using a viral vector. The new gene is inserted into the viral genome, the virus binds to the cell membrane and enters the cell by endocytosis. The viral genome, containing the new gene is injected into the cell nucleus, where the viral DNA is transcribed, starting the process of protein synthesis.

Lesson Summary

- In humans, whereas many genetic disorders are inherited in a recessive manner, simple dominant inheritance accounts for many of a person's physical characteristics.
- Genetic diseases may also be dominantly inherited, such as with achondroplasia.
- Genetic diseases may be due to specific mutations within a gene or to large chromosomal abnormalities.
- Traits controlled by genes located on the sex chromosomes (X and Y) are called sex-linked traits.
- Any recessive allele on the X chromosome of a male will not be masked by a dominant allele.
- Codominance is when two alleles are both expressed in the heterozygous individual.
- Incomplete dominance is seen in heterozygous individuals with an intermediate phenotype.
- Traits controlled by more than two alleles have multiple alleles.
- Many genes have multiple phenotypic effects, a property called pleiotropy.
- Epistasis is when a gene at one location (locus) alters the phenotypic expression of a gene at another locus.
- Polygenic traits are due to the actions of more than one gene and often, their interaction with the environment.
- Trisomy is a state where humans have an extra autosome; they have three of a particular chromosome instead of two.
- The most common trisomy in viable births is Trisomy 21 (Down Syndrome).
- Prenatal diagnosis refers to the diagnosis of a disease or condition before the baby is born.
- Amniocentesis and choronic villus sampling are invasive methods involved in prenatal diagnosis.
- Gene therapy is the insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele.

Review Questions

1. What is a genetic disease?
2. Discuss the main difference between autosomal and sex-linked.
3. Why is variation within the human genome important?
4. Why is it more common for males to have X-linked disorders?
5. Describe how a mutation can lead to a genetic disease.
6. Discuss how a new mutation can become a new dominant allele.
7. How are autosomal traits usually inherited? Give examples of traits.
8. How are genetic diseases usually inherited? Are there exceptions? Give examples.
9. Discuss the difference between codominance and incomplete dominance. Give exam-

ples.

10. What is meant by trisomy? **(Beginning)** How can trisomy phenotypes be detected?
11. What is the most common viable trisomy disorder?
12. List conditions involving an abnormal number of sex chromosomes.
13. Why is genetic counseling important?
14. What is gene therapy?
15. Describe the most common approach to gene therapy.

Further Reading / Supplemental Links

- The National Human Genome research Institute:
- http://www.genome.gov
- The Dolan DNA Learning Center:
- http://www.dnalc.org/home_alternate.html
- DNA Interactive:
- http://www.dnai.org/
- A Science Odyssey: DNA Workshop:
- http://www.pbs.org/wgbh/aso/tryit/dna/
- Kimball's Biology Pages:
- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages
- http://en.wikipedia.org

Vocabulary

achondroplasia An autosomal dominant disorder; the most common cause of dwarfism.

amniocentesis A prenatal diagnostic procedure in which a small amount of amniotic fluid, which contains fetal tissues, is extracted from the amnion or amniotic sac surrounding a developing fetus, so that the fetal DNA is examined for genetic abnormalities.

autosomal dominant disorder A disorder in which only one mutated allele is needed for a person to be affected.

autosomal recessive disorder A disorder in which both copies of the gene must be mutated for a person to be affected.

autosome Any chromosome other than a sex chromosome.

chorionic villus sampling (CVS) A prenatal diagnostic procedure which involves removing a sample of the chorionic villus (placental tissue) and testing it.

codominance When two alleles are both expressed in the heterozygous individual; both alleles affect the phenotype in separate and distinguishable ways.

cystic fibrosis (CF) A recessive inheritable disorder caused by a mutation in a gene called the cystic fibrosis transmembrane conductance regulator (CFTR).

Duchenne muscular dystrophy (DMD) The most common type of muscular dystrophy; an X-linked recessive disorder.

epistasis When a gene at one location (locus) alters the phenotypic expression of a gene at another locus.

gene therapy The insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele.

genetic counseling The process by which individuals or their families who are at risk of an inherited disorder are counseled on many different aspects of the disorder.

genetic counselor An individual trained in human genetics and counseling.

hemophilia A group of diseases in which blood does not clot normally.

incomplete dominance Occurs in heterozygous individuals with an intermediate phenotype; neither allele is dominant over the other.

Klinefelter's syndrome Caused by the presence of one or more extra copies of the X chromosome in a male's cells.

multiple allele traits Traits controlled by more than two alleles.

muscular dystrophy A term encompassing a variety of muscle wasting diseases.

mutation A change in the nucleotide sequence of DNA or RNA.

nondisjunction The failure of replicated chromosomes to separate during anaphase II of meiosis.

pedigree A chart which shows all of the known individuals within a family with a particular phenotype; a representation of genetic inheritance.

Phenylketonuria (PKU) An autosomal recessive genetic disorder characterized the inability to metabolize the amino acid phenylalanine.

pleiotropy Having multiple phenotypic effects.

polygenic traits Traits that are due to the actions of more than one gene and often, their interaction with the environment.

prenatal diagnosis The diagnosis of a disease or condition in a developing baby; done before the baby is born.

Severe Combined Immunodeficiency (SCID) A heritable immunodeficiency; a genetic disorder that cripples the immune system.

sex chromosomes Specify an organism's genetic sex; in humans, the X and Y chromosomes.

sex-linked traits Traits controlled by genes located on the sex chromosomes (X and Y).

Tay-Sachs disease An autosomal recessive genetic disorder that is fatal in early childhood; results from the accumulation of harmful quantities of fat in the nerve cells of the brain.

trisomy A state where humans have an extra autosome, having 47 chromosomes instead of 46. For example, trisomy 16 results in a third chromosome 16.

trisomy 21 Down syndrome; individuals often have some degree of mental retardation, some impairment of physical growth, and a specific facial appearance.

trisomy X Triple X syndrome; results from an extra copy of the X chromosome in each of a female's cells.

X-linked disorder A disorder caused by a mutation in a gene on the X chromosome; may be dominant or recessive, though the majority of X-linked disorders are recessive.

Y-linked disorder A disorder caused by a mutation in a gene on the Y chromosome; only affects males.

Points to Consider

In this chapter, we discussed human genetics as involved in human health. In the next chapter, we will discuss biotechnology. With gene therapy, we can see how biotechnology will play a significant role in society's future.

- Can you speculate on the role of biotechnology in our future?
- What other roles for biotechnology do you envision?
- Why is biotechnology important?

Image Sources

(1) Erin Ryan. http://commons.wikimedia.org/wiki/Image:Brushfield_eyes.jpg. Public Domain.

(2) NIH. http://commons.wikimedia.org/wiki/Image:Autodominant.jpg. Public Domain.

(3) NIH. http://en.wikipedia.org/wiki/File:XlinkRecessive.jpg. Public Domain.

(4) NASA. http://en.wikipedia.org/wiki/Image:Earlobes_free_attached.jpg. Public Domain.

(5) Rob Kay. *Boy with Down Syndrome assembling a bookcase.*. GNU-FDL.

(6) http://commons.wikimedia.org/wiki/File:CFtreatmentvest2.JPG. GNU-FDL.

(7) http://en.wikipedia.org/wiki/Image:Human_genome_to_genes.png. CC-BY 2.0.

(8) *sex_chromosomes.cfm?key=sex%20chromosome* . Public Domain.

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(10) http://www.genome.gov/Pages/Hyperion/DIR/VIP/Glossary/Illustration/chromosome.cfm?key=chromosome. Public Domain.

(11) NIH. http://commons.wikimedia.org/wiki/Image:Autorecessive.jpg. Public Domain.

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Chapter 10

Biotechnology

10.1 Lesson 10.1: DNA Technology

Lesson Objectives

- What is meant by DNA technology?
- What is the Human Genome Project?
- Describe the goals of the Human Genome Project.
- Describe gene cloning and the processes involved.
- What is PCR?
- Describe the processes involved in PCR.

Introduction

Is it really possible to clone people? Another question is, should we clone people? Are scientific fantasies, such as depicted on TV shows such as *Star Trek* or in the movie *GATTACA*, actually a possibility? Who can really say? How, really, will science affect our future? The answers partially lie in the field of biotechnology.

Biotechnology is technology based on biological applications. These applications are increasingly used in medicine, agriculture and food science. Biotechnology combines many features of biology, including genetics, molecular biology, biochemistry, embryology, and cell biology. Many aspects of biotechnology center around DNA and its applications, otherwise known as DNA technology. We could devote a whole textbook to current applications of biotechnology; in this chapter, however, we will focus on the applications towards medicine and the extension into the forensic sciences. First, though, we need to understand DNA technology.

DNA Technology

What is DNA technology? Is it using and manipulating DNA to help people? Is it using DNA to make better medicines and individualized treatments? Is it analyzing DNA to determine predispositions to genetic diseases? The answers to these questions, and many more, is yes. And the answers to many of these issues begin with the Human Genome Project.

The Human Genome Project

If we are all 99.9% genetically identical, what makes us different? How does that 0.1% make us tall or short, light or dark, develop cancer or not? To understand that 0.1%, we also need to understand the other 99.9%. Understanding the human genome is the goal of **The Human Genome Project (HGP)**. This project, publicly funded by the United States Department of Energy (DOE) (**Figure** 10.1); and the National Human Genome Research Institute (NHGRI), part of the National Institutes of Health (NIH), may be one of the landmark scientific events of our lifetime. *Our Molecular Selves* video discusses the human genome, and is available at http://www.genome.gov/25520211.

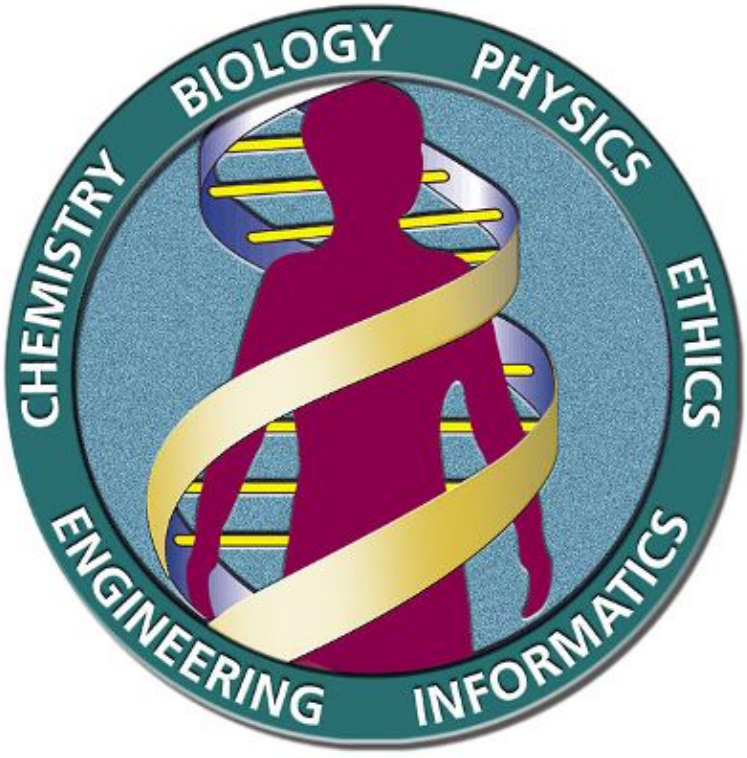

Figure 10.1: The Human Genome Project logo of the DOE.

The goal of the HGP is to understand the genetic make-up of the human species by deter-

mining the DNA sequence of the human genome (**Figure** 10.2);and the genome of a few model organisms. However, it is not just determining the 3 billion bases; it is understanding what they mean. Today, all 3 billion base pairs have been sequenced, and the genes in that sequence are in the process of being identified and characterized. A preliminary estimate of the number of genes in the human genome is around 22,000 to 23,000.

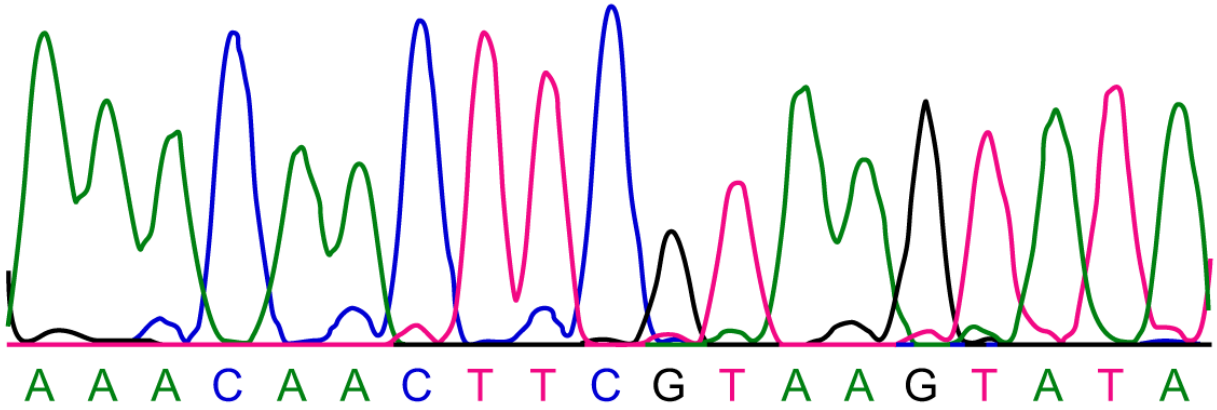

Figure 10.2: A depiction of DNA sequence analysis. Note the 4 colors utilized, each representing a separate base.

The sequence of the human DNA is stored in databases available to anyone on the Internet. The U.S. National Center for Biotechnology Information (NCBI), part of the NIH, as well as comparable organizations in Europe and Japan, maintain the genomic sequences in a database known as **Genbank**. Protein sequences are also maintained in this database. The sequences in these databases are the combined sequences of anonymous donors, and as such do not yet address the individual differences that make us unique. However, the known sequence does lay the foundation to identify the unique differences among all of us. Most of the currently identified variations among individuals will be **single nucleotide polymorphisms**, or SNPs. A **SNP** (pronounced "snip") is a DNA sequence variation occurring at a single nucleotide in the genome. For example, two sequenced DNA fragments from different individuals, GGATCTA to GGATTTA, contain a difference in a single nucleotide. If this base change occurs in a gene, the base change then results in two alleles: the C allele and the T allele. Remember an allele is an alternative form of a gene. Almost all common SNPs have only two alleles. The effect of these SNPs on protein structure and function, and any effect on the resulting phenotype, is an extensive field of study.

Gene Cloning

You probably have heard of cloning. Whereas cloning of humans has many ethical issues associated with it, the cloning of genes has been ongoing for well over 30 years, with cloning

of animals occurring more recently. **Gene cloning**, also known as molecular cloning, refers to the process of isolating a DNA sequence of interest for the purpose of making multiple copies of it. The identical copies are clones. In 1973, Stanley Cohen and Herbert Boyer developed techniques to make recombinant DNA, a form of artificial DNA.

Recombinant DNA is engineered through the combination of two or more DNA strands, combining DNA sequences which would not normally occur together. In other words, selected DNA (or the DNA of "interest") is inserted into an existing organismal genome, such as a bacterial plasmid DNA or some other sort of vector. The recombinant DNA can then be inserted into another cell, such as a bacterial cell, for amplification and possibly production of the resulting protein. This process is called **transformation**, the genetic alteration of a cell resulting from the uptake, incorporation, and expression of foreign genetic material. Recombinant DNA technology was made possible by the discovery of restriction endonucleases.

Restriction Enzyme Digestion and Ligation

In the classical **restriction enzyme** digestion and ligation cloning protocols, cloning of any DNA fragment essentially involves four steps:

1. isolation of the DNA of interest (or target DNA)
2. ligation
3. transfection (or transformation)
4. a screening/selection procedure.

For an overview of cloning, see http://www.hhmi.org/biointeractive/media/DNAi_genetic_eng-sm.mov.

Isolation of DNA

Initially, the DNA fragment to be cloned needs to be isolated. This DNA of interest may be a gene, part of a gene, a promoter, or another segment of DNA, and is frequently isolated by the Polymerase Chain Reaction (PCR) or restriction enzyme digestion. A **restriction enzyme** (or **restriction endonuclease**) is an enzyme that cuts double-stranded DNA at a specific sequence (**Table** 10.1). The enzyme makes two incisions, one through each strand of the double helix, without damaging the nitrogenous bases. This produces either overlapping ends (also known as sticky ends) or blunt ends.

Table 10.1:

A.	$G^{\downarrow}AATTC$	B.	$CCC^{\downarrow}GGG$
	$CTTAA_{\uparrow}G$		$GGG_{\uparrow}CCC$

A. *Eco*RI digestion produces overlapping "sticky" ends: The enzyme cleaves between the G and A on both strands. B. *Sma*II restriction enzyme cleavage produces "blunt" ends. The enzyme cleaves between the G and C on both strands.

(*Source: Created by:* Doug Wilkin, *License:* CC-BY-SA)

The 1978 Nobel Prize in Medicine was awarded to Daniel Nathans and Hamilton Smith for the discovery of restriction endonucleases. The first practical use of their work was the manipulation of *E. coli* bacteria to produce human insulin for diabetics.

Ligation

Once the DNA of interest is isolated, a ligation procedure is necessary to insert the amplified fragment into a vector to produce the recombinant DNA molecule. Restriction fragments (or a fragment and a plasmid/vector) can be spliced together, provided their ends are complementary. Blunt end ligation is also possible.

The **plasmid** or vector (which is usually circular) is digested with restriction enzymes, opening up the vector to allow insertion of the target DNA. The two DNAs are then incubated with **DNA ligase**, an enzyme that can attach together strands of DNA with double strand breaks. This produces the recombinant DNA molecule. **Figure** 10.3 depicts a plasmid with two additional segments of DNA ligated into the plasmid, producing the recombinant DNA molecule. **Figure** 10.4 depicts DNA before and after ligation.

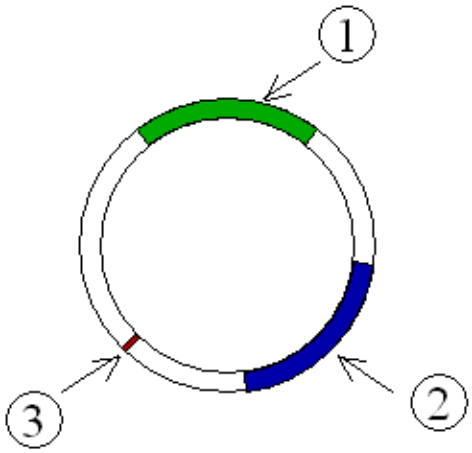

Figure 10.3: This image shows a line drawing of a plasmid. The plasmid is drawn as two concentric circles that are very close together, with two large segments and one small segment depicted. The two large segments (1 and 2) indicate antibiotic resistances usually used in a screening procedure, and the small segment (3) indicates an origin of replication. The resulting DNA is a recombinant DNA molecule.

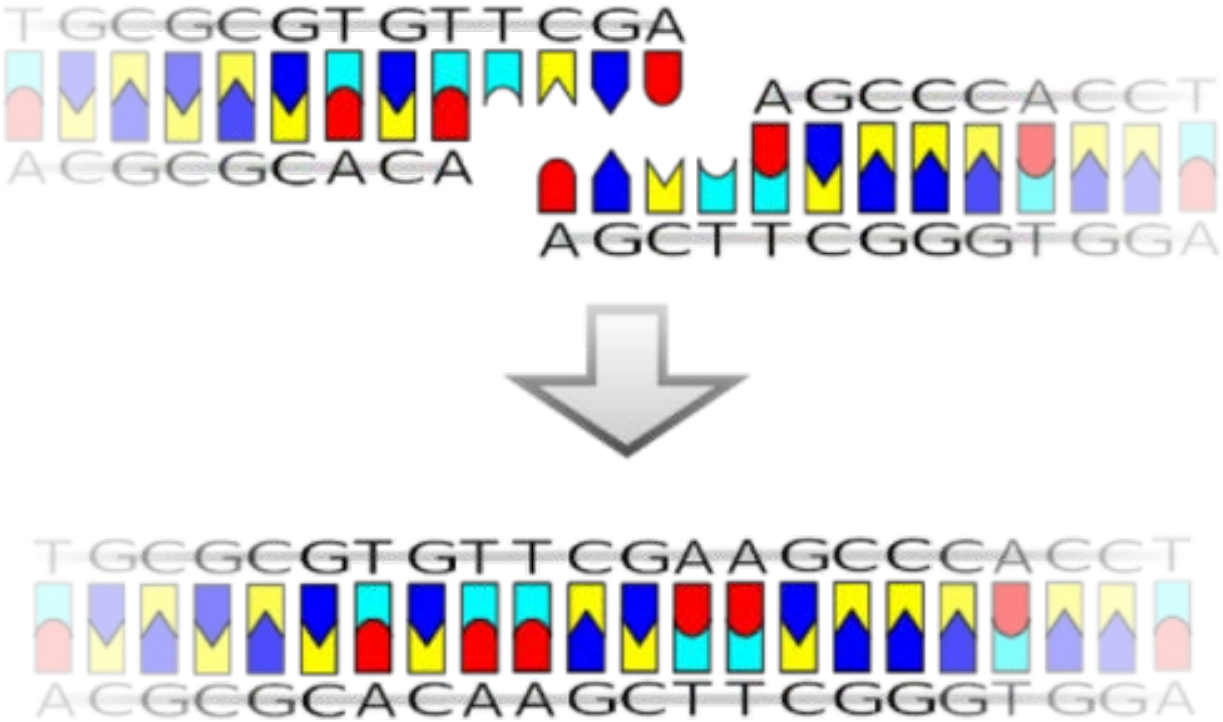

Figure 10.4: Sticky ends produced by restriction enzyme digestion can be joined with the enzyme DNA ligase.

Transfection and Selection

Following ligation, the recombinant DNA is placed into a host cell, usually bacterial, in a process called **transfection** or **transformation**. Finally, the transfected cells are cultured. Many of these cultures may not contain a plasmid with the target DNA as the transfection process is not usually 100% successful, so the appropriate cultures with the DNA of interest must be selected. Many plasmids/vectors include selectable markers - usually some sort of antibiotic resistance (**Figure** 10.3). When cultures are grown in the presence of an antibiotic, only bacteria transfected with the vector containing resistance to that antibiotic should grow. However, these selection procedures do not guarantee that the DNA of insert is present in the cells. Further analysis of the resulting colonies is required to confirm that cloning was successful. This may be accomplished by means of a process known as PCR (see below) or restriction fragment analysis, both of which need to be followed by gel electrophoresis and/or DNA sequencing (DNA sequence analysis).

DNA sequence analysis (the analysis of the order of the nitrogenous bases that make up the DNA), PCR, or restriction fragment analysis will all determine if the plasmid/vector contains the insert. Restriction fragment analysis is digestion of isolated plasmid/vector DNA with restriction enzymes. If the isolated DNA contains the target DNA, that fragment will be excised by the restriction enzyme digestion. Gel electrophoresis will separate DNA molecules based on size and charge. Examples are shown in **Figure** 10.5.

Gel Electrophoresis

Gel electrophoresis is an analytical technique used to separate DNA fragments by size and charge. Notice in **Figure** 10.5 that the "gels" are rectangular in shape. The gels are made of a gelatin-like material of either agarose or polyacrylamide. An electric field, with a positive charge applied at one end of the gel, and a negative charge at the other end, forces the fragments to migrate through the gel. DNA molecules migrate from negative to positive charges due to the net negative charge of the phosphate groups in the DNA backbone. Longer molecules migrate more slowly through the gel matrix. After the separation is completed, DNA fragments of different lengths can be visualized using a fluorescent dye specific for DNA, such as ethidium bromide. The resulting stained gel shows bands correspond to DNA molecules of different lengths, which also correspond to different molecular weights. Band size is usually determined by comparison to DNA ladders containing DNA fragments of known length. Gel electrophoresis can also be used to separate RNA molecules and proteins.

The Polymerase Chain Reaction

The **Polymerase Chain Reaction** (PCR) is used to amplify specific regions of a DNA strand millions of times. A region may be a number of loci, a single gene, a part of a gene, or a non-coding sequence. This technique produces a useful quantity of DNA for analysis,

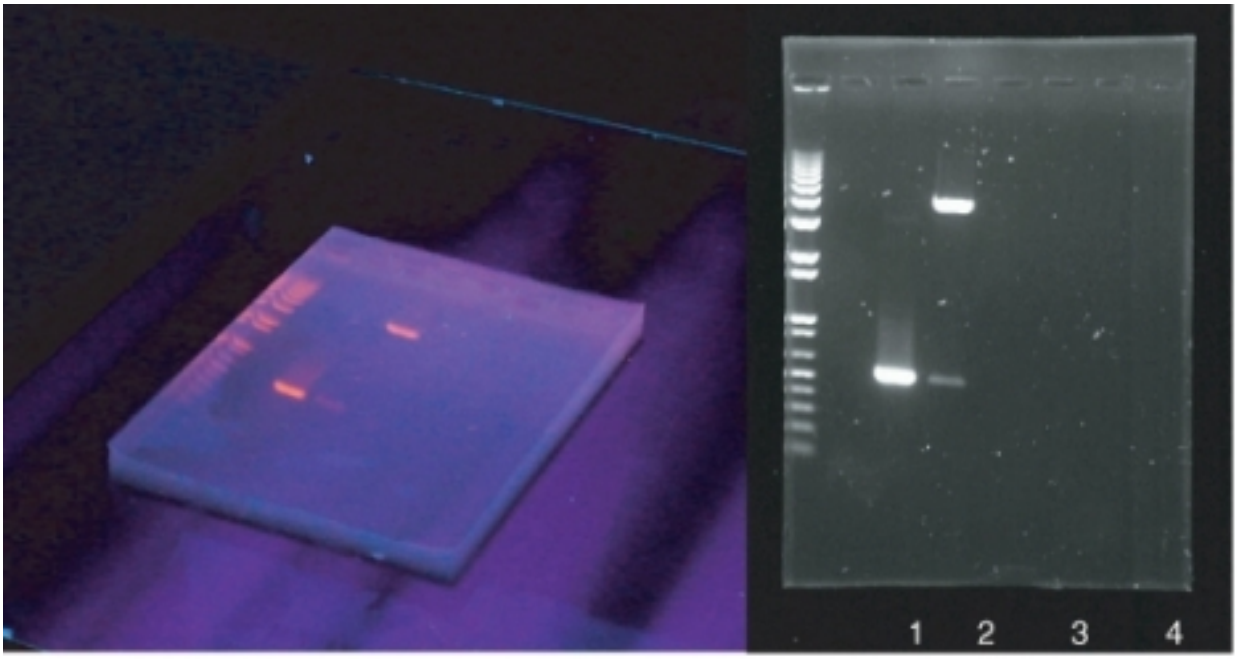

Figure 10.5: Agarose gel following agarose gel electrophoresis on UV light box: In the gel with UV illumination (left), the ethidium bromide stained DNA glows pink; Right, photo of a gel. Far left: DNA ladder of fragments of known length. Lane 1: A PCR product of just over 500 bases. Lane 2: Restriction digest showing the 500 base fragment cut from a 4.5 kb plasmid vector.

be it medical, forensic or some other form of analysis. Amplification of DNA from as little as a single cell is possible. Whole genome amplification is also possible.

PCR utilizes a heat stable DNA polymerase, **Taq polymerase**, named after the thermophilic bacterium *Thermus aquaticus,* from which it was originally isolated. *T. aquaticus* is a bacterium that lives in hot springs and hydrothermal vents, and Taq polymerase is able to withstand the high temperatures required to denature DNA during PCR (discussed below). Taq polymerase's optimum temperature for activity is between 75°C and 80°C. Recently other DNA polymerases have also been used for PCR.

A basic PCR involves a series of repeating cycles involving three main steps (see **Figure** 10.6):

1. denaturation of the double stranded DNA
2. annealing of specific oligonucleotide primers
3. extension of the primers to amplify the region of DNA of interest

These steps will be discussed in additional detail below.

The oligonucleotide primers are single stranded pieces of DNA that correspond to the 5' and 3' ends of the DNA region to be amplified. These primers will anneal to the corresponding segment of denatured DNA. Taq Polymerase, in the presence of free deoxynucleotide triphosphates (dNTPs), will extend the primers to create double stranded DNA. After many cycles of denaturation, annealing and extension, the region between the two primers will be amplified.

The PCR is commonly carried out in a thermal cycler, a machine that automatically allows heating and cooling of the reactions to control the temperature required at each reaction step (see below). The PCR usually consists of a series of about 30 to 35 cycles. Most commonly, PCR is carried out in three repeating steps, with some modifications for the first and last step.

PCR is usually performed in small tubes or wells in a tray, each often beginning with the complete genome of the species being studied. As only a specific sequence from that genome is of interest, the sequence specific primers are targeted to that sequence. PCR is done with all the building blocks necessary to create DNA: template DNA, primers, dNTPs, and a polymerase.

The three basic steps of PCR (**Figure** 10.6) are:

- Denaturation step: This step is the first regular cycling event and consists of heating the reaction to 94 - 98°C for 30 to 60 seconds. It disrupts the hydrogen bonds between complementary bases of the DNA strands, yielding single strands of DNA.
- Annealing step: The reaction temperature is lowered to 50-65°C for 30 to 60 seconds, allowing annealing of the primers to the single-stranded DNA template. Stable hydrogen bonds form between the DNA strand (the template) and the primers when the

primer sequence very closely matches the complementary template sequence. Primers are usually 17 - 22 nucleotides long and are carefully designed to bind to only one site in the genome. The polymerase binds to the primer-template hybrid and begins DNA synthesis.
- Extension step: A temperature of around 72°C is used for this step, which is close to the optimum temperature of Taq polymerase. At this step the Taq polymerase extends the primer by adding dNTPs, using one DNA strand as a template to create a the other (new) DNA strand. The extension time depends on the length of the DNA fragment to be amplified. As a standard, at its optimum temperature, the DNA polymerase will polymerize a thousand bases in one minute.

Utilizing the PCR, DNA can be amplified millions of times to generate quantities of DNA that can be used for a number of purposes. These include the use of DNA for prenatal or genetic testing, such as testing for a specific mutation. PCR has revolutionized the fields of biotechnology, human genetics, and a number of other sciences. Many of the applications will be discussed in the following lesson. PCR was developed in 1983 by Kary Mullis. Due to the importance of this process and the significance it has had on scientific research, Dr. Mullis was awarded the Nobel Prize in Chemistry in 1993, just 10 years after his discovery.

To say that PCR, molecular cloning and the Human Genome Project has revolutionized biology and medicine would be an understatement. These efforts have led to numerous accolades, including Nobel prizes, and more may follow. Some of the ways that these discoveries have shaped our lives are the focus of the next lesson.

Lesson Summary

- Biotechnology is technology based on biological applications, combining many features of Biology including genetics, molecular biology, biochemistry, embryology, and cell biology.
- The goal of the Human Genome Project is to understand the genetic make-up of the human species by determining the DNA sequence of the human genome and the genome of a few model organisms.
- Gene cloning, also known as molecular cloning, refers to the process of isolating a DNA sequence of interest for the purpose of making multiple copies of it (cloning).
- Classic gene cloning involves the following steps:

1. Restriction enzyme digestion and ligation
2. Isolation of DNA
3. Ligation
4. Transfection and Selection
5. Gel electrophoresis

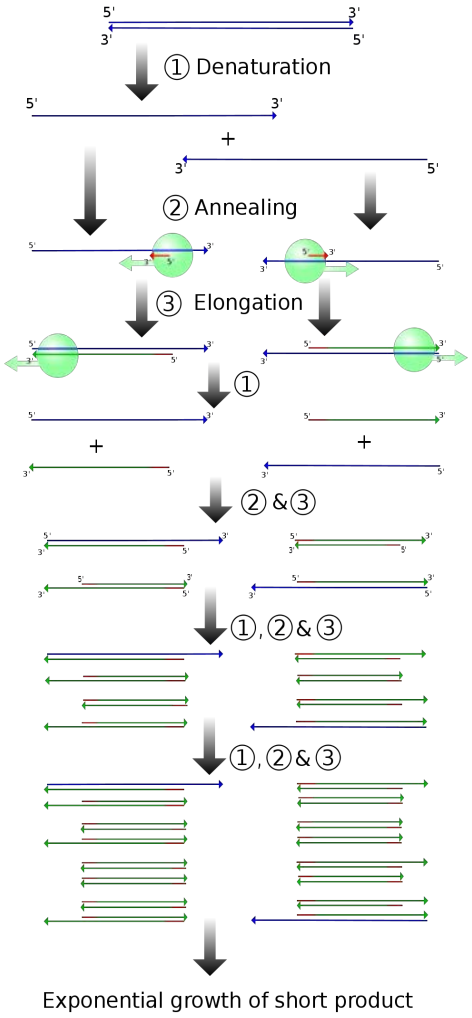

Figure 10.6: PCR: A repeating cycle of denaturation (1), annealing (2), and extension (3). Notice that initially there is a double strand of DNA, and after denaturation, the DNA is single stranded. In the annealing step (2), single stranded primers bind. These primers are extended by Taq Polymerase, represented by the green ball (3).

- The Polymerase Chain Reaction (PCR) is used to amplify millions of times specific regions of a DNA strand. This can be a number of loci, a single gene, a part of a gene, or a non-coding sequence.
- PCR usually involves the following steps:

1. Denaturation step
2. Annealing step
3. Extension step

Review Questions

1. Why are biotechnology and DNA technology considered the same?
2. What are the goals of the Human Genome Project?
3. Is the DNA sequence information generated by the HGP available to anyone, and if so, how?
4. How are gene cloning and recombinant DNA related?
5. Describe the process of gene cloning.
6. How does gel electrophoresis analyze DNA?
7. What is PCR?
8. What allows PCR to be done at high temperatures?
9. Describe the PCR process.

Further Reading / Supplemental Links

- http://www.genome.gov/HGP
- http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml
- http://biotech.about.com/od/cloning/tp/DNAcloning.htm
- http://croptechnology.unl.edu/viewLesson.cgi?LessonID=957884601
- http://www.pcrstation.com/
- http://nobelprize.org/educational_games/chemistry/pcr/index.html
- http://en.wikipedia.org
- http://www.vtaide.com/png/cloning.htm

Vocabulary

biotechnology Technology based on biological applications.

gel electrophoresis An analytical technique used to separate DNA fragments by size and charge.

Genbank The U.S. National Center for Biotechnology Information, part of the National Institutes of Health, which maintains the genomic sequences in a database.

gene cloning The process of isolating a DNA sequence of interest for the purpose of making multiple copies of it.

The Human Genome Project A project to understand the genetic make-up of the human species by determining the DNA sequence of the human genome and the genome of a few model organisms.

plasmid (or vector) A small circular piece of DNA that carries the recombinant DNA into a host organism for cloning.

polymerase chain reaction (PCR) A repeating series of cycles used to amplify millions of times specific regions of a DNA strand.

recombinant DNA Engineered through the combination of two or more DNA strands that combine DNA sequences which would not normally occur together.

restriction enzyme (or restriction endonuclease) An enzyme that cuts double-stranded DNA.

Taq polymerase Named after the thermophilic bacterium *Thermus aquaticus* from which it was originally isolated, is the heat-stable polymerase used in the PCR reaction.

Points to Consider

- The Human Genome Project, gene cloning, and PCR are some of the most remarkable scientific achievements of the recent past. But how can these milestones make our lives better?
- Medicine and food science are just two of the categories that benefit from biotechnology. Speculate on how our lives are made better by these achievements.

10.2 Lesson 10.2: Biotechnology

Lesson Objectives

- Describe various applications of biotechnology as related to medicine, agriculture and forensic science.

- How is DNA technology related to genetic testing and prenatal diagnosis?
- Why is biotechnology so important in agriculture?
- Why is DNA analysis the most important tool of the forensic scientist?
- Describe forensic STR analysis.
- Discuss some of the ELSI associated with biotechnology.

Introduction

Scientists have sequenced a consensus version of the human genome. Now what? Do we know what all the genes are or what they do? Not yet. Do we know what phenotypes are associated with mutations in the genes? For many genes, or even most genes, we do not. Do we even know exactly how many genes we have? Not exactly. And we are far away from knowing what makes us all unique. So how does this information help us? The Human Genome Project has been labeled a landmark scientific event. But what can we do with this information?

There are many applications of genetic information, including applications in medicine and agriculture. The applications of genetics to forensic science have become one of the most important aspects of the criminal justice system. And of course, these applications raise many ethical questions. These applications and questions will be the focus of this lesson.

Applications of DNA Technology: Medicine

As discussed in the first lesson of this chapter, the Human Genome Project has opened up many applications to take advantage of what we know about our genome in order to help us. Many of these applications are medically related. Others will be legally related. And yet still other uses of DNA technology include those in agriculture and the food sciences.

Understanding and curing genetic diseases is the ultimate goal of human geneticists. As discussed in the Human Genetics chapter, gene therapy is the insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele. Of course, the findings of the Human Genome Project are significant in determining the disease-causing alleles.

In the 1920s, there was no known way to produce insulin, which was needed by people to remove excess sugar from the bloodstream. People with diabetes either lack insulin, produce low levels of insulin, or are resistant to insulin, and thus they may need external insulin to control blood glucose levels. This problem was solved, at least temporarily, when it was found that insulin from a pig's pancreas could be used in humans. This method was the primary solution for diabetes until recently. The problem with insulin production was raised again: there were not enough pigs to provide the quantities of insulin needed. Scientists needed to devise another way. This led to one of the biggest breakthroughs in recombinant DNA technology: the cloning of the human insulin gene.

By methods discussed in the first lesson in this chapter, the specific gene sequence that codes for human insulin was introduced into the bacteria *E. coli*. The transformed gene altered the genetic makeup of the bacterial cells, such that in a 24 hour period, billions of *E. coli* containing the human insulin gene resulted, producing human insulin to be administered to patients.

Though the production of human insulin by recombinant DNA procedures is an extremely significant event, many other aspects of DNA technology are beginning to become reality. In medicine, modern biotechnology provides significant applications in such areas as pharmacogenomics, genetic testing (and prenatal diagnosis), and gene therapy. These applications use our knowledge of biology to improve our health and our lives. Many of these medical applications are based on the findings of the Human Genome Project.

Pharmacogenomics

Currently, millions of individuals with high cholesterol take a similar type of drug. You may know of people who take a medicine to help with their cholesterol levels. However, these drugs probably work slightly differently in many of those people. In some, it lowers their cholesterol significantly; in others it may lower it only moderately; and in some, it may have no effect at all. Why the difference? Because of the genetic background of all people. Pharmacogenomics, a combination of pharmacology and genomics (the study of the genome) that refers to the study of the relationship between pharmaceuticals and genetics, may explain and simplify this problem.

Pharmacogenomics is the study of how the genetic inheritance of an individual affects his or her body's response to drugs. In other words, pharmacogenomics will lead to the design and production of drugs that are adapted to each person's genetic makeup.

Pharmacogenomics will result in the following benefits:

1. Development of tailor-made medicines. Using pharmacogenomics, pharmaceutical companies will be able to create drugs based on the proteins, enzymes and RNA molecules that are associated with specific genes and diseases. These tailor-made drugs promise not only to maximize the beneficial effects of the medicine, but also to decrease damage to nearby healthy cells.
2. More accurate methods of determining appropriate drug dosages. Knowing a patient's genetics will enable doctors to determine how well his or her body can process and metabolize a medicine. This will allow doctors to prescribe the proper levels of the medicine, allowing the medicine to have optimal results.
3. Improvements in the drug discovery and approval process. Once the genes and proteins associated with a disease are known, the discovery of new medicines will be made easier using these genes and proteins as targets for the medicine. In addition to creating much more beneficial medicines, this could significantly shorten the drug discovery process.

4. Better vaccines. Safer vaccines can be designed and produced by organisms transformed with DNA sequences from an antigen. These vaccines will trigger the immune response without the risks of infection. They will be capable of being engineered to carry several strains of pathogen at once, combining several vaccines into one.

Genetic Testing and Prenatal Diagnosis

Let's propose a hypothetical situation: unfortunately, your family is predisposed to develop a genetic disease. You and your spouse want to have a baby, but you want to know the likelihood of the child developing the disease.

This scenario could happen to anyone. As we learn more and more about disease causing genes, it will become easier to test for mutations in those genes. Currently, is there any way to determine if a baby will develop a disease due to a known mutation? Is it possible to screen for a mutation in a developing baby? Yes.

Genetic testing involves the direct examination of DNA sequences. A scientist scans, by any number of methods, a patient's DNA for mutated sequences. Genetic testing can be used to:

- Diagnose a disease.
- Confirm a diagnosis.
- Provide information about the course of a disease.
- Confirm the existence of a disease.
- Predict the risk of future development of a disease in otherwise healthy individuals or their children.
- Identify carriers (unaffected individuals who are heterozygous for a recessive disease gene).
- Perform prenatal diagnostic screening.
- Perform newborn screening.

Consultations with human geneticists and genetic counselors are an important first step in genetic testing. They will most likely prescribe some sort of prenatal screening (see the *Human Genetics* chapter). **Prenatal screening** (also known as **prenatal diagnosis** or testing) is the testing for diseases or conditions in a fetus or embryo before it is born. Methods may involve amniocentesis or chorionic villus sampling to remove fetal cells. DNA can be isolated from these cells and analyzed. If the mutation that results in the phenotype is known, that specific mutation can be tested, either through restriction fragment length polymorphism analysis or, more likely, through PCR and DNA sequence analysis. As it is the baby's DNA that is being analyzed, the analysis will determine if the developing baby will have the mutation and develop the phenotype, or not have the mutation. Parents can then be informed of the probability of the baby developing the disease.

In human genetics, **preimplantation genetic diagnosis** (PIGD) is genetic analysis performed on embryos prior to implantation. PIGD is considered an alternative to prenatal diagnosis. Its main advantage is that it avoids selective pregnancy termination, as the method makes it highly likely that the baby will be free of the disease in question. In PIGD, *in vitro* fertilization is used to obtain embryos for analysis. DNA is isolated from developing embryos prior to implantation, and specific genetic loci are screened for mutations, usually using PCR based analysis. Embryos that lack the specific mutation can then be implanted into the mother, thereby guaranteeing that the developing baby will not have the specific mutation analyzed for (and thus not have the disease associated with that mutation).

Applications of DNA Technology: Agriculture

Biotechnology has many other useful applications besides those that are medically related. Many of these are in agriculture and food science. These include the development of **transgenic crops** - the placement of genes into plants to give the crop a beneficial trait. Benefits include:

- Improved yield from crops.
- Reduced vulnerability of crops to environmental stresses.
- Increased nutritional qualities of food crops.
- Improved taste, texture or appearance of food.
- Reduced dependence on fertilizers, pesticides and other agrochemicals.
- Production of vaccines.

Improved Yield from Crops

Using biotechnology techniques, one or two genes may be transferred into a crop to give a new trait to that crop. This is done in the hope of increasing its yield. However, these increases in yield have proved to be difficult to achieve. Current genetic engineering techniques work best for single gene effects - that is traits inherited in a simple Mendelian fashion. Many of the genetic characteristics associated with crop yield, such as enhanced growth, are controlled by a large number of genes, each of which just has a slight effect on the overall yield. There is, therefore, still much research, including genetic research, to be done in this area.

Reduced Vulnerability to Environmental Stresses

Crops are obviously dependent on environmental conditions. Drought can destroy crop yields, as can too much rain or floods. But what if crops could be developed to withstand these harsh conditions? Biotechnology will allow the development of crops containing genes that will enable them to withstand biotic and abiotic stresses. For example, drought and excessively salty soil are two significant factors affecting crop productivity. But there are

crops that can withstand these harsh conditions. Why? Probably because of that plant's genetics. So biotechnologists are studying plants that can cope with these extreme conditions, trying to identify and isolate the genes that control these beneficial traits. The genes could then be transferred into more desirable crops, with the hope of producing the same phenotypes in those crops.

Thale cress (**Figure** 10.7), a species of *Arabidopsis (Arabidopsis thaliana)*, is a tiny weed that is often used for plant research because it is very easy to grow and its genome has been extensively characterized. Scientists have identified a gene from this plant, At-DBF2, that confers resistance to some environmental stresses. When this gene is inserted into tomato and tobacco cells, the cells were able to withstand environmental stresses like salt, drought, cold and heat far better than ordinary cells. If these preliminary results prove successful in larger trials, then At-DBF2 genes could help in engineering crops that can better withstand harsh environments. Researchers have also created transgenic rice plants that are resistant to rice yellow mottle virus (RYMV). In Africa, this virus destroys much of the rice crops and makes the surviving plants more susceptible to fungal infections.

Figure 10.7: Thale cress.

Increased Nutritional Qualities of Crops

Maybe you've heard over and over that eating beans is good for you. True? Well, maybe. But what if it were possible to increase the nutritional qualities of food? One would think that would be beneficial to society. So, can biotechnology be used to do just that? Scientists

are working on modifying proteins in foods to increase their nutritional qualities. Also, proteins in legumes and cereals may be transformed to provide all the amino acids needed by human beings for a balanced diet.

Improved Taste, Texture or Appearance of Food

Have you ever gone to the grocery store, bought some fruit and never gotten around to eating it? Maybe you haven't, but I bet your parents have. Modern biotechnology can be used to slow down the process of spoilage so that fruit can ripen longer on the plant and then be transported to the consumer with a still reasonable shelf life. This is extremely important in parts of the world where time from harvest to the consumer may be longer than in other areas. In addition to improving the taste, texture and appearance of fruit, it will also extend the usable life of the fruit. As the world population grows and grows, this may become a fairly important issue. Extending the life of fruit can expand the market for farmers in developing countries due to the reduction in spoilage. This has successfully been demonstrated in the tomato. The first genetically modified food product was a tomato which was transformed to delay its ripening. Researchers in Indonesia, Malaysia, Thailand, Philippines and Vietnam are currently working on delayed-ripening papayas.

Reduced Dependence on Fertilizers, Pesticides and Other Agrochemicals

There is growing concern regarding the use of pesticides in agriculture. Therefore, many of the current commercial applications of modern biotechnology in agriculture are focused on reducing the dependence of farmers on these chemicals. For example, *Bacillus thuringiensis* (Bt) is a soil bacterium that produces a protein that can act as an insecticide, known as the **Bt toxin**. But it is a protein, not a foreign chemical. Could this protein be used in crops instead of pesticides? Traditionally, an insecticidal spray has been produced from these bacteria. As a spray, the Bt toxin is in an inactive state and requires digestion by an insect to become active and have any effect. Crop plants have now been engineered to contain and express the genes for the Bt toxin, which they produce in its active form. When an insect ingests the transgenic crop, it stops feeding and soon thereafter dies as a result of the Bt toxin binding to its gut wall. Bt corn is now commercially available in a number of countries to control corn borer (a lepidopteran insect like moths and butterflies), which is otherwise controlled by insecticidal spraying.

In addition to insects, weeds have also been a menace to farmers - just ask anyone with a garden how much they hate weeds. They can quickly compete for water and nutrients needed by other plants. Sure, farmers can use herbicides to kill weeds, but do these chemicals also harm the crops? Can biotechnology help with this issue? Some crops have also been genetically engineered to acquire tolerance to the herbicides - allowing the crops to grow, but killing the weeds. But the lack of cost effective herbicides with a broad range of activity - that

Figure 10.8: Kenyans examining genetically modified insect resistant transgenic Bt corn.

do not harm crops - is a problem in weed management. Multiple applications of numerous herbicides are routinely needed to control the wide range of weeds that are harmful to crops. And at times these herbicides are being used as a preventive measure – that is, spraying to prevent weeds from developing rather than spraying after weeds form. So these chemicals are being added to crops. This practice is followed by mechanical and/or hand weeding to control weeds that are not controlled by the chemicals. Crops that are tolerant of herbicides would obviously be a tremendous benefit to farmers (**Figure** 10.8). The introduction of herbicide tolerant crops has the potential to reduce the number of chemicals needed during a growing season, thereby increasing crop yield due to improved weed management and decreased harm to the crops.

In 2001, 626,000 square kilometers of transgenic crops were planted. Seventy-seven percent of the transgenic crops were developed for herbicide tolerance in soybean, corn, and cotton, 15% were Bt crops for insect resistance, and 8% were developed with genes for both insect resistance and herbicide tolerance in cotton and corn.

Production of Vaccines in Crop Plants

Many little children hate shots. And many children in parts of the world do not even have access to vaccines. But what if these vaccines were available in an edible form? Modern biotechnology is increasingly being applied for novel uses other than food. Banana trees and tomato plants have been genetically engineered to produce vaccines in their fruit. If future clinical trials prove successful, the advantages of edible vaccines would be enormous, especially for developing countries. The transgenic plants could be grown locally and cheaply. Edible vaccines would not require the use of syringes, which, in addition to being unpleasant, can be a source of infections if contaminated.

Applications of DNA Technology: Animal Cloning

DNA technology has proved very beneficial to humans. **Transgenic animals** are animals that have incorporated a gene from another species into their genome (**Figure** 10.9). They are used as experimental models to perform phenotypic tests with genes whose function is unknown, or to generate animals that are susceptible to certain compounds or stresses for testing purposes. Other applications include the production of human hormones, such as insulin. Many times these animals are rodents, such as mice, or fruit flies (*Drosophila melanogaster*). Fruit flies are extremely useful as genetic models to study the effects of genetic changes on development.

But transgenic animals just have one novel gene. What about a whole new genome? It could be argued that human cloning is one of the techniques of modern biotechnology. It involves the removal of the nucleus from one cell and its placement in an unfertilized egg cell whose nucleus has either been deactivated or removed. Theoretically this would result

Figure 10.9: GloFish: the first genetically modified animal to be sold as a pet. GloFish are transgenic zebrafish transfected with a natural fluorescence gene.

in an individual genetically identical to the donor. Of course, there are many ethical issues associated with human cloning. But animal cloning is arguably a different story.

In February 1997, Ian Wilmut and his colleagues at the Roslin Institute announced the successful cloning of a sheep named Dolly from the mammary glands of an adult female (**Figure** 10.10). Dolly was the first mammal to be cloned from an adult somatic cell. The cloning of Dolly made it apparent to many that the techniques used to produce her could someday be used to clone human beings. This resulted in tremendous controversy because of its ethical implications. After cloning was successfully demonstrated by Dolly's creators, many other large mammals, including horses and bulls, were cloned. Cloning is now considered a promising tool for preserving endangered species.

Figure 10.10: Dolly the sheep and her first-born lamb Bonnie. Dolly was the first large mammal to be cloned. This picture shows that a cloned animal can perform many, if not all, of the same functions as a non-cloned animal.

In animal cloning, the nucleus from a somatic cell is inserted into an egg cell in which the nucleus has been removed. The resulting cell is cultivated and after a few divisions, the egg cell is placed into a uterus where it is allowed to develop into a fetus that is genetically

identical to the donor of the original nucleus (**Figure** 10.11). For an animation of cloning, see http://www.dnalc.org/resources/animations/cloning101.html.

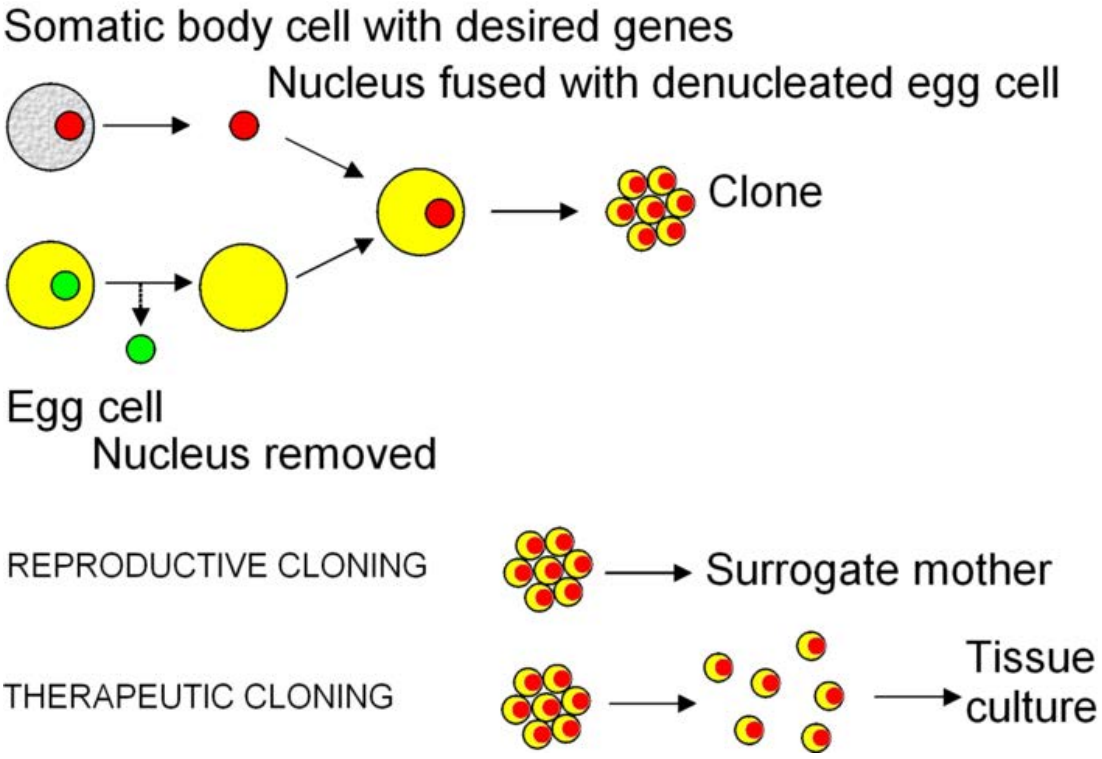

Figure 10.11: Reproductive cloning: The nucleus is removed from a somatic cell and fused with a denucleated egg cell. The resulting cell may develop into a colony of cloned cells, which is placed into a surrogate mother. In therapeutic cloning, the resulting cells are grown in tissue culture; an animal is not produced, but genetically identical cells are produced.

Applications of DNA Technology: Forensic DNA Analysis

You know that DNA can be used to distinguish individuals from each other. You may have heard that DNA can also be used to match evidence and suspects and help solve crimes. This is demonstrated on shows like *CSI: Crime Scene Investigation*. But how is this done? How is a "genetic fingerprint," a DNA pattern unique to each individual (except identical twins) created? **Genetic fingerprinting**, or **DNA fingerprinting**, distinguishes between individuals of the same species using only samples of their DNA. DNA fingerprinting has thus become one of the most powerful tools of the forensic scientist, enabling law enforcement personnel to match biological evidence from crime scenes to suspects. As any two humans have the majority of their DNA sequence in common, those sequences which demonstrate high variability must be analyzed. This DNA analysis was first developed using DNA hybridization techniques, but now is almost exclusively PCR-based.

DNA fingerprinting was developed by Sir Alec Jeffreys in 1985. Genetic fingerprinting exploits highly variable repeating sequences. Two categories of these sequences are microsatellites and minisatellites. **Microsatellites**, also known as **short tandem repeats** (STRs), consist of adjacent repeating units of 2 - 10 bases in length, for example $(GATC)_n$, where GATC is a tetranucleotide (4 base) repeat and n refers to the number of repeats. It is the number of repeating units at a given locus that is variable. An **STR profile** can be created for any individual by analyzing a series of STRs (**Figure** 10.12). Two unrelated humans will be unlikely to have the same numbers of repeats at a given locus.

In STR profiling, PCR is used to obtain enough DNA to then detect the number of repeats at 13 specific loci. PCR products are separated by gel or capillary electrophoresis. By examining enough STR loci and counting how many repeats of a specific STR sequence there are at a given locus, it is possible to create a unique genetic profile of an individual. STR analysis has become the prevalent analysis method for determining genetic profiles in forensic cases. It is possible to establish a match that is extremely unlikely to have arisen by coincidence, except in the case of identical twins, who will have identical genetic profiles. The polymorphisms (different in the number of repeats) displayed at each STR region will be shared by approximately 5 - 20% of individuals. When analyzing STRs at multiple loci, such as the 13 STRs analyzed in forensic DNA analysis, it is the unique combinations of these polymorphisms in an individual that makes this method unmatched as an identification tool. The more STR regions that are analyzed in an individual the more discriminating the test becomes.

Capillary electrophoresis is similar to gel electrophoresis but uses a capillary tube filled with the gelatin material.

Genetic fingerprinting is used in forensic science to match suspects to samples of blood, hair, saliva or semen, or other sources of DNA. It has also led to several exonerations of formerly convicted suspects. Genetic fingerprinting is also used for identifying human remains, testing for paternity, matching organ donors, studying populations of wild animals, and establishing the province or composition of foods. It has also been used to generate hypotheses on the pattern of the human migration.

In the United States, DNA fingerprint profiles generated from the 13 STR loci are stored in **CODIS**, The Combined DNA Index System, maintained by the Federal Bureau of Investigation. As of 2007, CODIS maintained over 4.5 million profiles. Profiles maintained in CODIS are compiled from both suspects and evidence, and therefore are used to help solve criminal cases. Profiles of missing persons are also maintained in CODIS. The true power of STR analysis is in its statistical power of discrimination. Because the 13 loci are independently assorted, the laws of probabilities can be applied. This means that if someone has the genotype of ABC at three independent loci, then the probability of having that specific genotype is the probability of having type A times the probability of having type B times the probability of having type C. This has resulted in the ability to generate match probabilities of 1 in a quintillion (1 with 18 zeros after it) or more, that is, the chance of two samples matching by coincidence is greater than the number of people on the planet, or the number

of people that have ever lived!

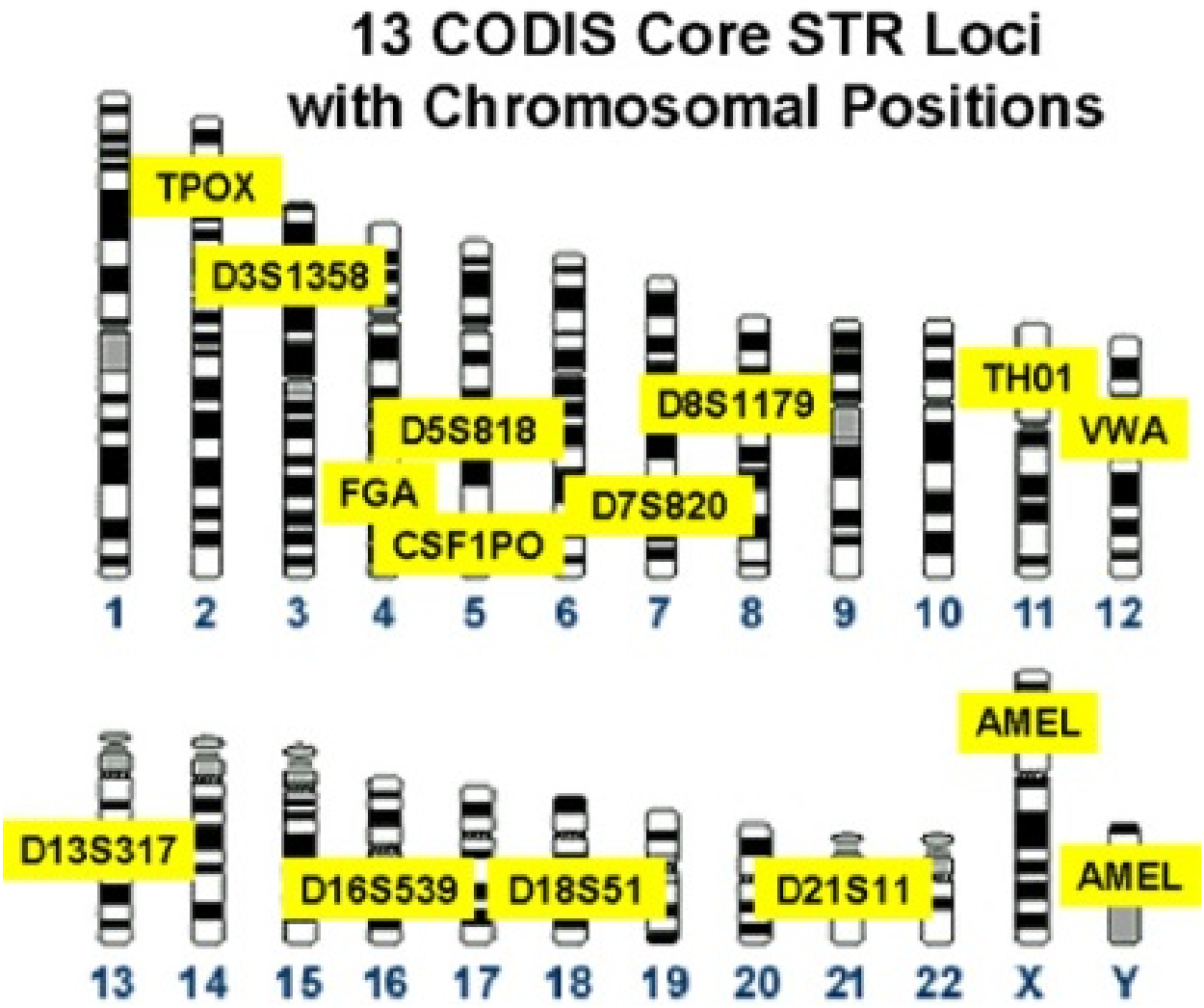

Figure 10.12: The CODIS loci analyzed by STR analysis. Notice they are spread over 14 chromosomes, and that two are on the X and Y chromosomes.

The development of PCR has enabled STR analysis to become the method of choice for DNA identification. Prior to PCR, other methods were utilized. These include restriction fragment length polymorphism (RFLP) analysis and Southern blot analysis.

RFLP Analysis: Restriction Fragment Length Polymorphism

Prior to the development of PCR, restriction enzyme digestion of DNA followed by Southern blot analysis was used for DNA fingerprinting. This analysis is based on the polymorphic nature of restriction enzyme sites among different individuals, hence **restriction fragment**

length polymorphisms are formed after digestion of DNA with these enzymes. A **Southern blot**, named after its inventor Edwin Southern, is a method used to check for the presence of a specific DNA sequence in a DNA sample. Once an individual's DNA is digested with a specific restriction enzyme, the resulting fragments are analyzed by Southern blot analysis. These fragments will produce a specific pattern for that individual. Southern blotting is also used for other molecular biology procedures, including gene identification and isolation. Other blotting methods that employ similar principles have been developed. These include the western blot and northern blot. These procedures analyze proteins and RNA respectively.

RFLP and Southern blot analysis involved several steps:

1. First, the DNA being analyzed is cut into different-sized pieces using restriction enzymes.
2. The resulting DNA fragments are separated by gel electrophoresis.
3. Next, an alkaline solution or heat is applied to the gel so that the DNA denatures and separates into single strands.
4. Nitrocellulose paper is pressed evenly against the gel and then baked so the DNA is permanently attached to it. The DNA is now ready to be analyzed using a radioactive single-stranded DNA probe in a hybridization reaction.
5. After hybridization, excess probe is washed from the membrane, and the pattern of hybridization is visualized on X-ray film by autoradiography (**Figure** 10.13).

Hybridization is when two genetic sequences bind together because of the hydrogen bonds that form between the base pairs. To make hybridization work, the radioactive probe has to be denatured so that it is single-stranded. The denatured probe and the Southern blot are incubated together, allowing the probe to bind to the corresponding fragment on the Southern blot. The probe will bond to the denatured DNA wherever it finds a fit. Hybridization of a probe made to a variable segment of DNA will produce a DNA fingerprint pattern specific for an individual. This procedure has a number of steps and is very labor intensive. PCR-based methods are much simpler.

Ethical, Legal, and Social Issues

Imagine someone analyzes part of your DNA. Who controls that information? What if your health insurance company found out you were predisposed to develop a devastating genetic disease. Might they decide to cancel your insurance?

Privacy issues concerning genetic information is a growing issue in this day and age, especially among those who donate DNA for large-scale sequence-variation studies. Other concerns have been to anticipate how the resulting data may affect concepts of race and ethnicity; identify potential uses (or misuses) of genetic data in workplaces, schools, and courts; identify

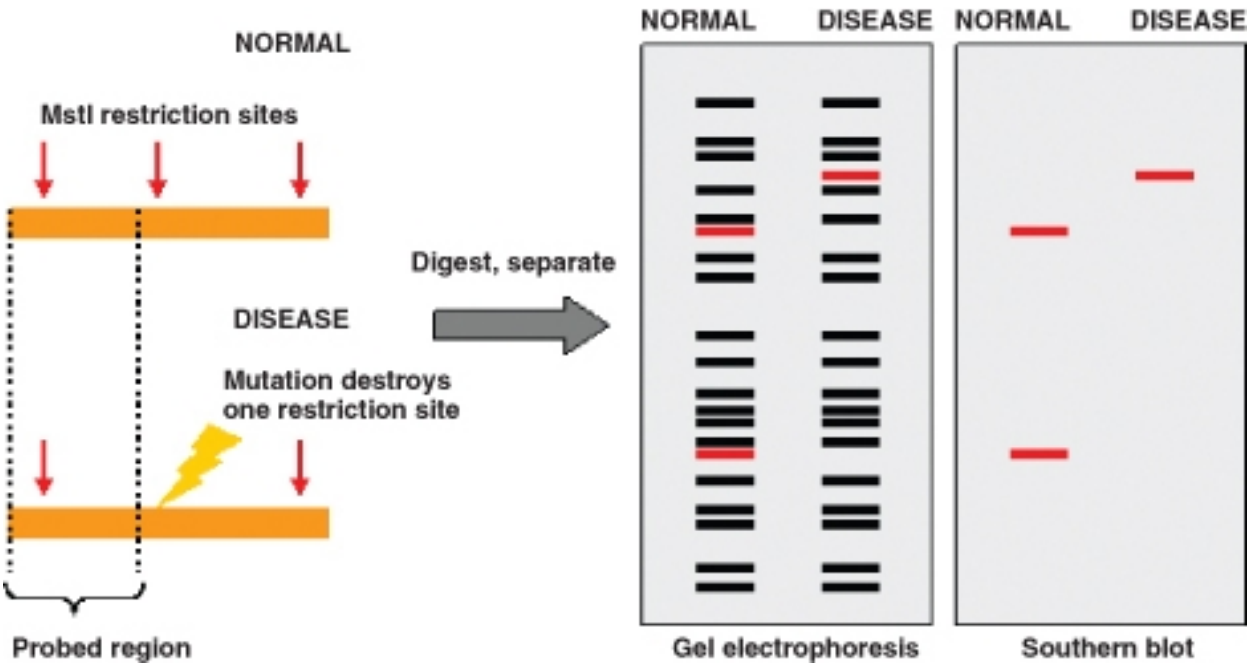

Figure 10.13: Mutations can create or abolish restriction enzyme (RE) recognition sites, thus affecting quantities and length of DNA fragments resulting from RE digestion.

commercial uses; and foresee impacts of genetic advances on the concepts of humanity and personal responsibility.

ELSI stands for Ethical, Legal and Social Issues. It's a term associated with the Human Genome project. This project didn't only have the goal to identify all the approximately 20,000 – 24,000 genes in the human genome, but also to address the ELSI that might arise from the project. The U.S. Department of Energy (DOE) and the National Human Genome Research Institute (NHGRI) of the National Institutes of Health (NIH) devoted 3% to 5% of their annual human genome research budget toward studying ethical, legal, and social issues surrounding the availability of your genetic information. This represents the world's largest bioethics program and has become a model for ELSI programs around the world.

Rapid advances in DNA-based research, human genetics, and their applications have resulted in new and complex ethical and legal issues for society. ELSI programs that identify and address these implications have been an integral part of the Human Genome Project since its inception. These programs have resulted in a body of work that promotes education and helps guide the conduct of genetic research and the development of related medical and public policies.

ELSI programs address the following issues, among others:

- Privacy and confidentiality issues concerning personal genetic information.

- The fairness in the use of personal genetic information by insurers, employers, courts, schools, adoption agencies, and the military, among others.
- The psychological impact and stigmatization due to an individual's genetic differences.
- Clinical issues. These include the education of doctors and other health service providers, patients, and the general public in the capabilities and uses of genetic information, and the scientific/medical limitations of genetic testing. Clinical issues also include the implementation of standards and quality-control measures in genetic testing procedures.
- Reproductive issues. These include adequate informed consent for complex and potentially controversial procedures, and the use of genetic information in making decisions concerning reproductive options.
- Uncertainties associated with genetic testing. The current and future uncertainties associated with testing for susceptibilities to a genetic condition raise many ethical issues, as does the testing for predisposition to a complex condition (such as heart disease) linked to multiple genes and gene-environment interactions.
- Health and environmental issues concerning genetically modified foods and microbes.
- Commercialization of genetic products including property rights, such as patents and copyrights, and issues concerning the accessibility to genetic data and materials.

Biotechnology will have a tremendous impact on our future - of this there is no doubt. Is society entering some dangerous areas? Well, many of these issues have never been analyzed until now. With the discovery of countless amounts of genetic information and the development of its applications, many questions need to be addressed.

- Who should have access to personal genetic information, and how will it be used?
- Who owns and controls genetic information?
- How does personal genetic information affect an individual and society's perceptions of that individual?
- How does genomic information affect members of minority communities?
- How reliable and useful is fetal genetic testing?
- How will genetic tests be evaluated and regulated for accuracy, reliability, and utility?
- How do we prepare the public to make informed choices?
- Should testing be performed when no treatment is available?
- Should parents have the right to have their minor children tested for adult-onset diseases?
- Are genetic tests reliable and interpretable by the medical community?
- Where is the line between medical treatment and enhancement?
- Are genetically modified foods and other products safe for humans and the environment?
- How will these technologies affect developing nations' dependence on the West?
- Who owns genes and other pieces of DNA?
- Will patenting DNA sequences limit their accessibility and development into useful products?

Are scientific fantasies, such as those depicted on TV shows such as *Star Trek* or in the movie *GATTACA*, a possibility? Who can really say? How, really, will biotechnology affect our future? It seems as if the possibilities are endless.

Lesson Summary

- In medicine, modern biotechnology provides significant applications in such areas as pharmacogenomics, genetic testing (prenatal diagnosis), and gene therapy.
- Pharmacogenomics, the combination of pharmacology and genomics, is the study of the relationship between pharmaceuticals and genetics.
- Pharmacogenomics will result in the following benefits:

1. Development of tailor-made medicines.
2. More accurate methods of determining appropriate drug dosages.
3. Improvements in the drug discovery and approval process.
4. Better vaccines.

- Genetic testing involves the direct examination of DNA sequences.
- Genetic testing can be used to: diagnose a disease; confirm a diagnosis; provide prognostic information about the course of a disease; confirm the existence of a disease; predict the risk of future development of a disease in otherwise healthy individuals or their children; screen for carriers (unaffected individuals who are heterozygous for a disease gene); perform prenatal diagnostic screening; and perform newborn screening.
- Biotechnology in agriculture includes the development of transgenic crops - the placement of genes into plants to give the crop a beneficial trait. Benefits include improved yield from crops, reduced vulnerability of crops to environmental stresses, increased nutritional qualities of food crops, improved taste, texture or appearance of food, reduced dependence on fertilizers, pesticides and other agrochemicals, and production of vaccines.
- Transgenic animals are animals that have incorporated a gene from another species into their genome. They are used as experimental models to perform phenotypic tests with genes whose function is unknown, or to generate animals that are susceptible to certain compounds or stresses for testing purposes. Other applications include the production of human hormones, such as insulin.
- Animal cloning is the generation of genetically identical animals using DNA from a donor animal, not a gamete. Dolly, a sheep, was the first mammal to be cloned from an adult somatic cell.
- Genetic fingerprinting, or DNA fingerprinting, distinguishes between individuals of the same species using only samples of their DNA. DNA fingerprinting has thus become one of the most powerful tools of the forensic scientist, enabling law enforcement personnel to match biological evidence from crime scenes to suspects.

- ELSI stands for Ethical, Legal and Social Issues. This is a term associated with the Human Genome project. Rapid advances in DNA-based research, human genetics, and their applications have resulted in new and complex ethical and legal issues for society. ELSI programs that identify and address these implications have been an integral part of the Human Genome Project since its inception. These programs have resulted in a body of work that promotes education and helps guide the conduct of genetic research and the development of related medical and public policies.

Review Questions

1. List applications of DNA technology.
2. List how DNA technology is used in agriculture.
3. How is DNA technology used in medicine?
4. What are some of the benefits of pharmacogenomics?
5. Describe how pharmacogenomics will result in specialty medicines.
6. What are potential uses of genetic testing?
7. Describe how DNA technology can improve yield from crops.
8. Describe how DNA technology can be used to reduce vulnerability to environmental stresses. Why is this important? State an example.
9. What is the difference between a transgenic animal and a cloned animal?
10. Who was Dolly? Why was she important?
11. What is a DNA fingerprint and how is it used?
12. What is STR profiling?
13. Describe why ELSI programs are important.
14. List some ELSI issues.

Further Reading / Supplemental Links

- http://www.genome.gov
- http://www.dna.gov/basics/http://www.ornl.gov/sci/techresources/Human_Genome/medicine/pharma.shtml
- http://www.ornl.gov/sci/techresources/Human_Genome/medicine/pharma.shtml
- http://www.ornl.gov/sci/techresources/Human_Genome/medicine/genetherapy.shtml
- http://www.ama-assn.org/ama/pub/category/2306.html
- http://www.americanheart.org/presenter.jhtml?identifier=4566
- http://www.ift.org/cms/
- http://www.pub.ac.za/projects/dnakits.html
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- http://www.genome.gov/ELSI/
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- http://en.wikipedia.org/wiki/Main_Page

Vocabulary

CODIS The Combined DNA Index System, is maintained by the Federal Bureau of Investigation and stores DNA profiles.

ELSI Ethical, Legal and Social Issues. This term is associated with the Human Genome Project.

genetic fingerprinting (DNA fingerprinting) Creates a unique DNA pattern that distinguishes between individuals of the same species using only samples of their DNA.

genetic testing The direct examination of DNA sequences for mutated sequence.

microsatellites (short tandem repeats) Adjacent repeating units of 2 - 10 bases in length, for example $(GATC)_n$, where GATC is a tetranucleotide repeat and n refers to the number of repeats.

pharmacogenomics The combination of pharmacology and genomics, is the study of the relationship between pharmaceuticals and genetics. It is the study of how the genetic inheritance of an individual affects his or her body's response to drugs.

preimplantation genetic diagnosis (PGD) Genetic analysis performed on embryos prior to implantation.

prenatal diagnosis (prenatal screening) Testing for diseases or conditions in a fetus or embryo before it is born. Methods may involve amniocentesis or chorionic villus sampling to remove fetal cells.

restriction fragment length polymorphism (RFLP) Analysis that analyzes the differences between restriction enzyme sites.

southern blot Named after its inventor Edwin Southern, is a method used to check for the presence of a specific DNA sequence in a DNA sample.

STR profiling Analyzes 13 STR loci to create a DNA profile utilized in forensic analysis.

transgenic animals Animals that have incorporated a gene from another species into their genome.

transgenic crops The result of placement of genes into plants to give the crop a beneficial trait.

Points to Consider

We have spent the past few chapters discussing genetics, molecular biology, and their implications. These are implicitly related to evolution.

- Can you hypothesize on the relationship between genetics and evolution?
- Why is an understanding of the principals of DNA and inheritance essential to understand evolution?

Image Sources

(1) The Roslin Institute. http://en.wikipedia.org/wiki/Image:Dolly_the_sheep2-thumb.jpg.

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Chapter 11

History of Life

11.1 Lesson 11.1: Studying the History of Life

Lesson Objectives

- Use the conditions required for fossilization to explain why fossils are rare.
- List and give examples of different types of fossils.
- Discuss the way in which index fossils contribute to our understanding of the history of life.
- Compare relative dating of fossils and rock layers to absolute dating.
- Explain why "carbon dating" is an inadequate description of aging rocks and fossils.
- Describe how molecular clocks clarify evolutionary relationships.
- Compare and contrast Geologic Time with absolute time. Include limits of each.
- Sequence the levels of organization of the Geologic Time Scale from largest to smallest.
- Arrange the four major Eons and one Supereon from youngest to oldest.
- Describe and interpret the differences in fossil abundance throughout the Geologic Time Scale.
- Distinguish macroevolution from microevolution and explain their relationship.
- Describe the general pattern of the fossil record to support Darwin's idea that all life descended from a common ancestor.
- Evaluate the role of mass extinctions and episodic speciation in evolution.
- Identify types of major environmental change in the earth's history and relate them to patterns in the fossil record.
- Analyze ways in which the Geologic Time Scale may give false impressions of the history of life.
- Discuss rates of macroevolution and speciation, comparing and contrasting the ideas of gradualism, punctuated equilibrium and quantum evolution.
- Compare and contrast adaptive radiation (divergent evolution) to convergent evolution.

- Indicate some changes in geography which influence evolution.
- Use patterns of evolution and environmental change to account for worldwide differences in the distribution of mammals (placentals vs. marsupials).
- Define and give examples of coevolution.

Introduction

"There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved." **- Charles Darwin, *Origin of Species.* 1859**

The history of life as we currently understand it is vast and wondrous and dramatic and humbling and ennobling. Vast is the almost unimaginable expanse of time during which life has flourished: four billion years is our current best estimate! Wondrous is the diversity of species throughout that time: some 30 million species occupy Earth today, and over 90% of all which have ever lived are extinct. Dramatic are the tales of change in environment and in diversity: ice ages, volcanism, continental drift, mass extinction, and bursts of evolutionary creativity have all shaped the natural environment. Humbling is the recognition that humans have played a relatively small part in the history; if the 4.6 billion-year story of Earth is reduced to a single **cosmological day,** humans occupy just the last minute and a half, and civilization covers less than the final second (**Figure** 11.1). Ennobling is the story's revelation that we are related to and interdependent with all other species – back 4 billion years to "so simple a beginning" (**Figure** 11.25). Finally, the history of life suggests we might add one more striking impression: Terrifying is the realization that we are in many ways unique among species in our unprecedented power to change the environment, influence evolution, and destroy life's diversity.

If we as a species occupy just the last minute and one-half of the cosmological day, how can we know the vast history of that 4.6 billion-year "day?" How did we arrive at 4.6 billion years as the age of the earth? How we know is the topic of this first lesson on the history of life.

Tools: The Fossil Record, Aging the Ages, and Molecular Clocks

By age three, you probably knew that dinosaurs are part of the history of life. Our understanding of where they belong in the tale is relatively recent, but "dragon bones" have been known for thousands of years in China and Europe. **Fossils** are preserved remains or traces of organisms that provide extremely rare but vivid windows to the past. Because most parts of organisms decompose rapidly following death, fossilization is an exceptionally uncommon

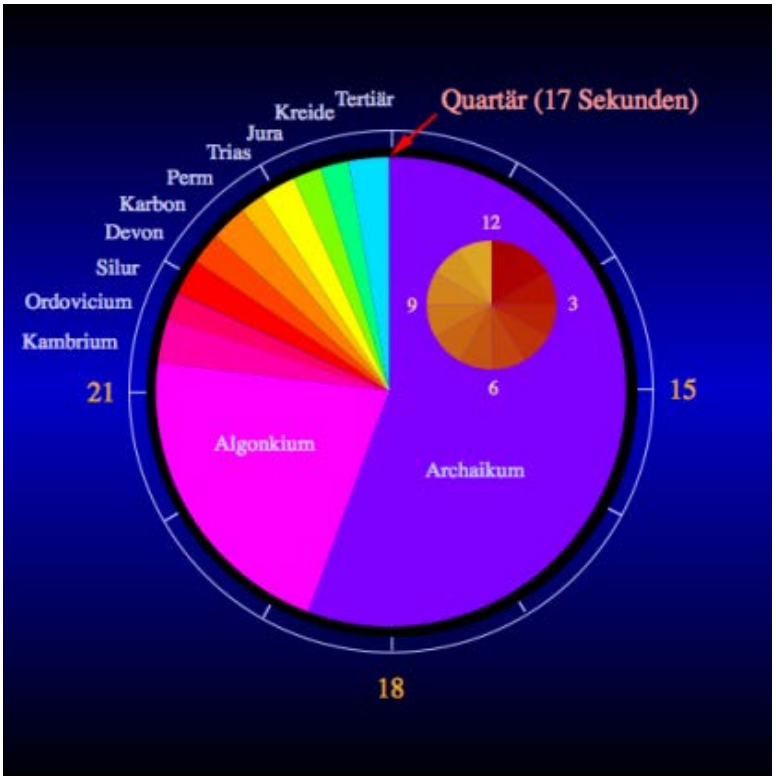

Figure 11.1: This Earth clock condenses the 4.5 billion years of earth's history into a single 24-hour day. German names mark major geologic time periods. The last 17 seconds comprise the Quaternary period, spanning the past 2 million years. Human civilization appears only in the last second of the clock's 24 hours.

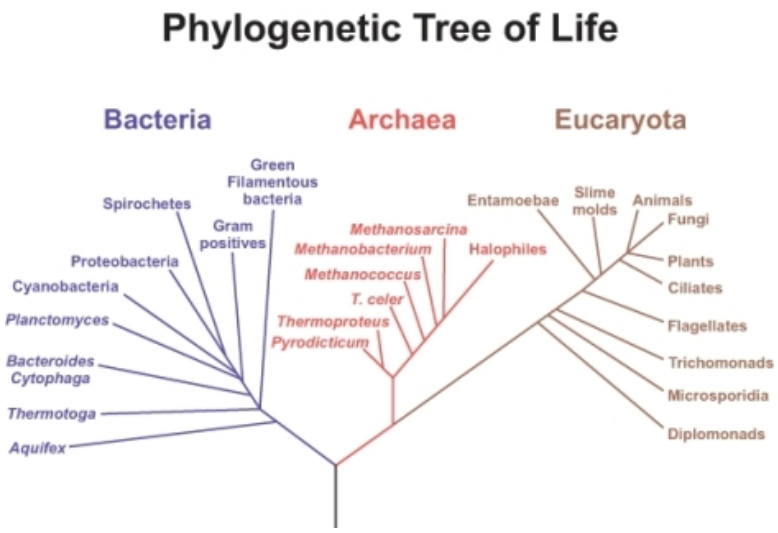

Figure 11.2: A family tree of living things summarizes our understanding of the history of life and shows that humans and animals share common ancestors with all of modern life. This diagram demonstrates our current understanding of evolutionary relationships. We will explore some of these relationships later in the chapter.

occurrence, and usually preserves only hard body parts, shown in **Figure** 11.3. Remains must be covered by sediment almost immediately. Buried organisms may experience mineralization (occasionally even within cells), or they may decay, leaving a space within the sediment later replaced with rock. Alternative pathways to fossilization include freezing, drying, trapping in resin (amber) or burial in anoxic (oxygen-free) environments. **Trace fossils** preserve footprints, burrows, droppings, eggs, nests, and other types of impressions. Overall, a great variety of types of fossils reveal the history of life, shown in **Figure** 11.4.

Images in rock tell us what kinds of organisms lived in the past, but the story of life cannot be told without knowing when various organisms appeared. **Paleontologists** use two methods to date fossils. The oldest method looks at position within a sedimentary column of rock to give a fossil's **relative age**. If the rock layers are undisturbed, the deepest layers are the oldest, and layers near the surface are the youngest, shown in **Figure** 11.5. Widespread, short-lived **index fossils** can help identify rock layers of the same age spread around the earth, shown in **Figure** 11.6. Combining worldwide observations of relative position and composition resulted in a **Geologic Time Scale** for the Earth – a column of rock layers which reflects the history of sedimentary rock formation and changing life, stretching back to a time which apparently held no life. The fossil record showed patterns which, combined with his observations of living species, led Charles Darwin to conclude that all life on Earth descended from a single, simple common ancestor.

Relative age, however, only begins the story. **Absolute aging**, also known as **absolute dating**, uses **radioactive isotopes,** whose known **half-lives** can be used to calculate the

Figure 11.3: was a small dinosaur from Early Cretaceous Italy. This fossil of a juvenile only a few inches long is considered one of the most important vertebrate fossils ever discovered, because unlike most, it preserved internal organs as well as hard structures. Fossilization of an organism is itself a very rare event; preservation of soft tissues is even less likely.

number of years which have elapsed since a rock formed. Radioactive decay is a random but exponential process. An isotope's half life gives the time period over which half of the material will decay to a different, relatively stable product, shown in **Figure** 11.7. The ratio of the original isotope to its decay product changes in a predictable way. This predictability allows the relative abundances of isotope and decay product to be used as a clock that measures the time from the incorporation of the isotope into a rock or a fossil to the present.

For example, half of a sample of Carbon-14 will decay to Nitrogen in 5,370 years. Cosmic rays cause the formation of Carbon-14 from the more common and stable Carbon-12 at a relatively constant rate, so carbon dioxide in the atmosphere contains relatively constant, predictable amounts. Organisms acquire carbon from various mechanisms – plants from CO_2, and animals and other heterotrophs through food chains. When an organism dies, its carbon intake stops, and existing Carbon-14 atoms decay exponentially, according to their 5,370-year half-life. The proportion of Carbon-14 in the organism's remains indicates the time lapsed since its death.

Table 11.1: **Isotopes Used to Measure Absolute Age of Rocks and Fossils**

Isotope	Decay Product	Half-life	Aging of Rocks or Fossils
Carbon-14	Nitrogen	5370 years	Up to 60,000 years
Uranium 238/235	Thorium/Protactinium	80,000/34,300 years	Hundreds of thousands of years

Table 11.1: (continued)

Isotope	Decay Product	Half-life	Aging of Rocks or Fossils
Potassium-40	Argon	1.3 billion years	Earth's oldest rocks
Uranium-238/235	Lead	4.5 billion /704 million years	1 million to > 4.5 billion years

Carbon-14 has a relatively short half-life, so its use for absolute dating is limited to a maximum of about 60,000 years. Other isotopes are used to reach deeper into geological time. Uranium-238 and Uranium-235 decay to different isotopes of lead with half-lives of 4.46 billion and 704 million years, respectively, and together allow dating of rocks between 1 million and over 4.5 billion years old. **Table** 11.1 shows some of the many isotopes can be used to study rocks throughout Earth's 4.6 billion year history.

Absolute aging techniques confirmed and brought into focus the rock layer story geologists and paleontologists had developed with relative dating. They pushed Earth's history back 4.6 billion years, and showed that complex life evolved after some two billion years in which bacteria alone populated the Earth.

Further confirmation of common ancestry included **molecular clocks,** which measure changes in DNA or proteins to indicate degrees of relationship among species. Comparing DNA sequences of several species of primates, for example, shows that chimpanzees are more closely related to humans than are gorillas or baboons, shown in **Table** 11.2. If we assume uniform rates of mutation, we can estimate not only degree of relationship, but time back to common ancestry. Because DNA sequences (and mutations) determine the sequence of amino acids in proteins, Hemoglobin and other proteins are also used as "clocks." Both DNA and protein clocks support a universal common ancestor for life, confirming the story which continues to unfold as new discoveries expand the fossil record. Molecular clocks, together with evidence from the fossil record, allows scientists to estimate how long ago various groups of organisms diverged evolutionarily from one another.

Table 11.2: **DNA "Clock" Comparison of Primates**

Species	% Difference in Nucleotide Sequence, Compared to Humans
Human	0
Chimpanzee	1.2
Gorilla	1.6
Baboon	6.6

Figure 11.4: Different types of fossils reveal the history of life. Clockwise from top left: Amber preserves an insect intact. Stone etches impressions of Edmontosaurus skin. Rock echoes a dinosaur's footprint. Fossilized eggs recall a dinosaur of Mongolia. LaBrea Tar Pits fossilized the remains of a rich diversity of ice age animals. Permafrost preserved this female mammoth calf for nearly 10,000 years.

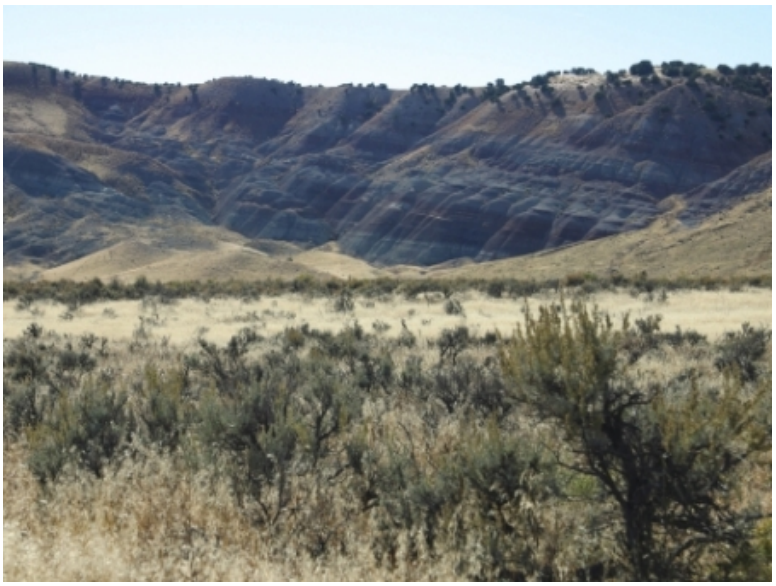

Figure 11.5: Relative aging dates sedimentary layers and the fossils they contain. Lower layers are older; upper layers are younger. Dinosaur fossils lie buried within this sedimentary formation in Green River, Utah.

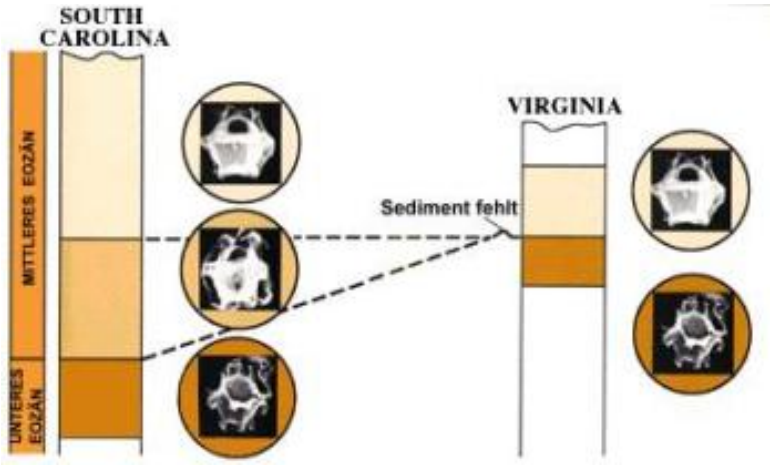

Figure 11.6: Single-celled algae serve as index fossils to correlate rock layers located in different states. The middle-aged rock layer in South Carolina has apparently eroded from a similar deposit of sedimentary rock in Virginia. Careful worldwide studies of relative age by many geologists and paleontologists led to the Geologic Time Scale.

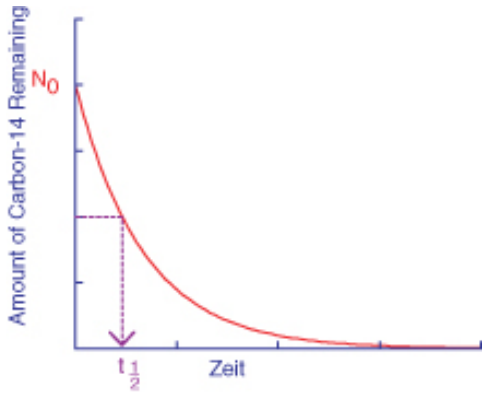

Figure 11.7: Exponential decay of a radioactive isotope such as carbon-14 occurs with a unique, predictable half-life (t½) of 5,370 years. The amount of carbon-14 remaining in a fossil organism thus indicates the time elapsed since death, giving a measure of absolute age.

A Geologic Time Scale Measures the Evolution of Life

We noted in the previous section that observation of rock layers, dating techniques, and correlation of similar strata from around the world led to the development of a Geologic Time Scale (**Figure** 11.8). How does the scale divide 4.6 billion years of history? What themes emerge from its stories of the past?

One theme is almost unimaginable amounts of time. The deep time of Earth's history is far beyond our experience, and our knowledge is far more detailed for recent millennia than for the distant past. A scale divided into evenly spaced periods of time would not show that detail. Instead, Geologic Time Scale divisions mark major events which highlight changes in climate, geography, atmosphere, and life. The largest units of time are **Eons**. Eons include smaller **Eras**, which in turn include **Periods, Epochs**, and **Stages**. Faunal stages identify specific fossil groups. Terms such as Upper/Late and Lower/Early divide parts of the scale into more recent and more distant subunits.

Four eons comprise the history of Earth, and their names refer to a second major theme of Earth history: the evolution of life. The Phanerozoic ("visible life") Eon spans the most recent 545 million years and includes three Eras well known for their chronicle of life: the oldest Paleozoic, middle Mesozoic, and current Cenozoic. The Proterozoic ("before complex life") Eon precedes the Phanerozoic, extending back 2.5 billion years. The Archean ("ancient") and Hadean ("unseen") Eons reach back to the formation of the Earth. The Precambrian **Supereon** combines the oldest three eons, and refers to the time before the first great explosion of life recorded in the fossil record - the **Cambrian** Period. The name "Cambrian" refers to Wales, where these fossils were first studied. Before this first period of the Phanerozoic, animals lacked hard body parts to contribute to the fossil record.

Figure 11.8: A linear arrangement of the Geologic Time Scale shows overall relationships between well-known time periods, which will be used in this and future chapters. Our knowledge of past life is concentrated in the most recent Eon, but the Phanerozoic occupies such a small proportion of the overall history of earth that eras, periods, and epochs are not precisely to scale. For future lessons, relevant parts of the scale will show more detail with greater accuracy.

Patterns and Processes of Macroevolution

Throughout geologic time, the fossil record reveals dramatic changes in species and groups of species which have populated the Earth. Evolution at or above the species level is **macroevolution**, in contrast to **microevolution**, which describes changes within a species or population. Many scientists no longer emphasize the distinction, believing evolution to be a single process which includes both patterns. However, themes from the Geologic Time Scale illustrate macroevolution, so we will consider its patterns and processes in this chapter.

Although fossils dated back only to the Cambrian during Darwin's time, radiometric dating has since identified fossil bacteria as old as the beginning of the Archean era 3.5 billion years ago. The geologic record shows over 2 billion years during which the only life was unicellular. The appearance of eukarytoic cells roughly 1.8 billion years ago marked a dramatic increase in cellular complexity. In rocks 1 billion years old, multicellular eukaryotes begin to appear, and by the end of the Precambrian, fossils record a variety of ancient multicellular organisms. The beginning of Cambrian Period marks an "explosion" of life, and in general, biodiversity has increased throughout the Phanerozoic, shown in **Figure** 11.9. Our current understanding of the fossil record confirms Darwin's ideas that life began as tiny single-celled bacteria and over vast time evolved to produce the complexity and diversity we celebrate today.

As recorded in fossils, the evolution of life was not smooth or steady. **Mass extinctions** and **episodic speciation** interrupted the overall pattern of increasing biodiversity, shown in **Figure** 11.9. These disruptions reflect dramatic changes in the environment of the Earth.

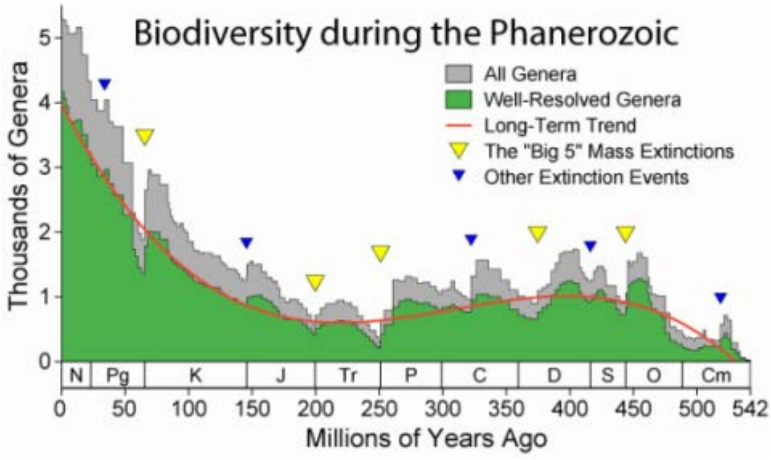

Figure 11.9: Estimates of numbers of marine genera throughout the last 542 million years support a gradual increase in biodiversity, interrupted by five major mass extinctions. Some scientists dispute the accuracy of such estimates, while others argue that they show regular cycles of extinction.

A major theme of the fossil record is loss of species. The death of a species – **extinction** – seems to be as much a characteristic of life as the death of individual organisms. Both

seem closely linked to change in environment. Through mutation or sexual reproduction, offspring show variation. Individuals whose variations are not well suited to their environment die. Those whose variations are adaptive survive to reproduce. Death and differential reproduction result in **adaptation** to a changing environment.

These same forces of **natural selection** inevitably affect species: the fossil record indicates that up to 99.9% of all species that have ever lived on Earth are now extinct. **Mass extinctions** involve most major groups of organisms over a short period. The past 550 million years, when fossils are sufficiently abundant to tell a reliable story, show five mass extinctions in which more than 50% of animal species died. The most famous is the extinction which ended the reign of the dinosaurs 65 million years ago. Accelerated evolution may follow mass extinction, because the empty ecological niches make way for new species. After the non-birdlike dinosaurs disappeared, mammals rapidly evolved to fill the available niches. The fossil record shows numerous examples of **episodic speciation**, a pattern of periodic increase which includes these rebounds as well as bursts of evolution following major new "discoveries" or "ideas" – for example, the biochemical pathways for photosynthesis or cellular respiration.

Closely related to mass extinction is the theme of major environmental change throughout Earth's history. Rock layers reflect critical changes in atmosphere and climate: oxidized iron deposits mark the introduction of oxygen gas to the atmosphere, and glacial deposits reflect periodic ice ages alternating with times of global warming. Craters and unique worldwide strata suggest that spectacular asteroid or comet collisions may have severely reduced solar radiation, and lava flows and ash suggests volcanism could have done the same. Massive geographic changes, now explained by **plate tectonics theory**, underlie volcanism as well as formation of new land bridges, seaways, and continents. Certain worldwide sedimentary deposits suggest significant sea level fluctuation, which may result from some of the aforementioned climate or plate tectonic changes. Life evolved against the backdrop of these often-catastrophic changes, and over 3.5 billion years of natural selection inevitably responded to them. Many of these changes are believed to have caused the mass extinctions and episodic speciation revealed in the fossil record. We will look at some of these events in more detail in the next two lessons.

Two caveats are critical in interpreting the history of life using the Geologic Time Scale. The first concerns the idea that evolution progresses via slow, steady, gradual change. We have already seen that mass extinction and episodic speciation interrupt the overall pattern of increasing biodiversity, but **gradualism** suggests that changes accumulate continuously as one species evolves to become another. An alternative, more recent theory, **punctuated equilibrium**, shown in **Figure** 11.10, proposes that species remain the same for long periods, and that change occurs infrequently but rather rapidly under unusual conditions such as geographic isolation or migration. The rather sudden appearance and disappearance of many individual species within the fossil record, noted even by Darwin, tends to support the latter theory. The idea of **quantum evolution** attempts to explain the origins of major groups (families, orders, and classes) as a response to drastic changes in environment or

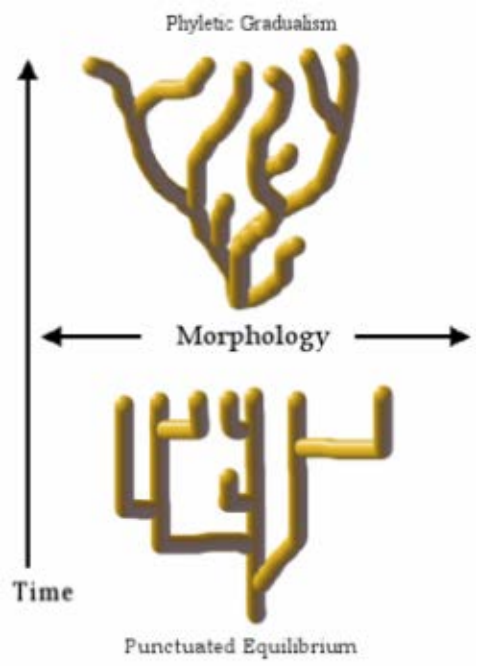

Figure 11.10: Two theories of evolutionary change - gradualism vs. punctuated equilibrium - are still debated. The former proposes continuous change, while the latter suggests that species remain constant for long periods of time and that change, when it occurs, is rapid.

adaptive zones. The fossil record supports great variation in the rate of evolutionary change - from group to group and even among closely related lineages. Each of these ideas about pattern and rate may accurately describe one of many ways evolution works.

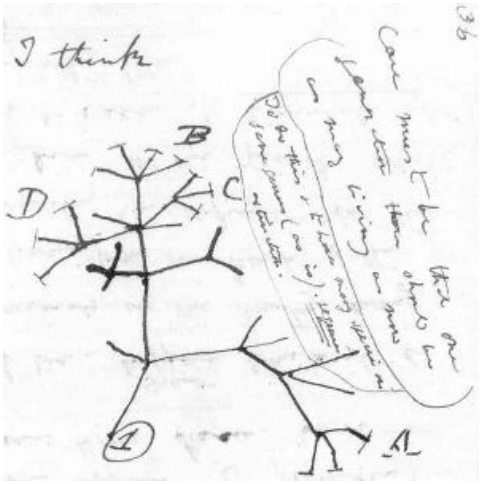

Figure 11.11: Charles Darwin's 1837 sketch from his First Notebook on Transmutation of Species (1837), shows the bush-like pattern of evolution.

A second caveat: the 4.6 billion year time scale makes it tempting to view evolution as linear, and perhaps even goal-directed. Time may be an arrow, but evolution is much more a bush of common ancestry–a family tree, as we saw at the beginning of the chapter. Darwin recognized this - his sketch, shown in **Figure** 11.11, shows the pattern of speciation predicted by his theory of chance variation and adaptive selection. A very recent (August 2007) discovery encourages us to view our own human ancestry as a bush rather than a line. Radiometric dating of a new fossil of *Homo habilis* shows that this species coexisted with the "more advanced" Homo erectus, shown in **Figure** 11.12. Previously, scientists considered the former an ancestor of the latter. The inappropriate expression "more advanced" implies the false, linear, goal-directed interpretation of evolution.

A famous example of "bushiness" in the history of life is **adaptive radiation**, a type of **divergent evolution.** This pattern of speciation involves the relatively rapid evolution from a single species to several species which fill a diversity of available ecological niches. Mass extinctions (the dinosaurs!), new volcanic islands (the Galapagos, or Hawaii), land bridge formation (the isthmus between North and South America) or "invention" of a new idea in evolution – all are events which "suddenly" open a variety of niches for adaptive radiation. In each case, a fundamental structure in one species is modified to serve new functions in different environments or modes of life. For example, forelimbs of mammals have become elongated with grasping hands for the forested habitats of monkeys, flattened into flippers for the aquatic habitats of whales, and spread into wings for the aerial habitats of bats, shown in **Figure** 11.13. Adaptive radiation explains – and the fossil record shows – that these groups all arose from one ancestor or a small group of common ancestors.

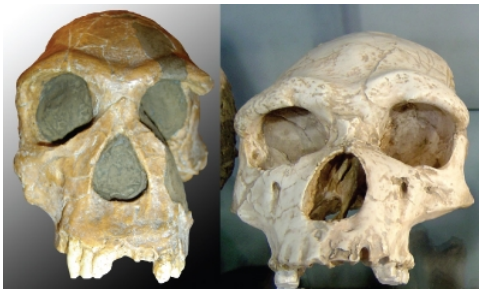

Figure 11.12: Homo habilis (left) was considered an ancestor to Homo erectus (right) until the 2007 discovery of a habilis fossil which showed that the two species coexisted. The history of the genus Homo, like the evolution of most species, is undoubtedly more bush-like than linear.

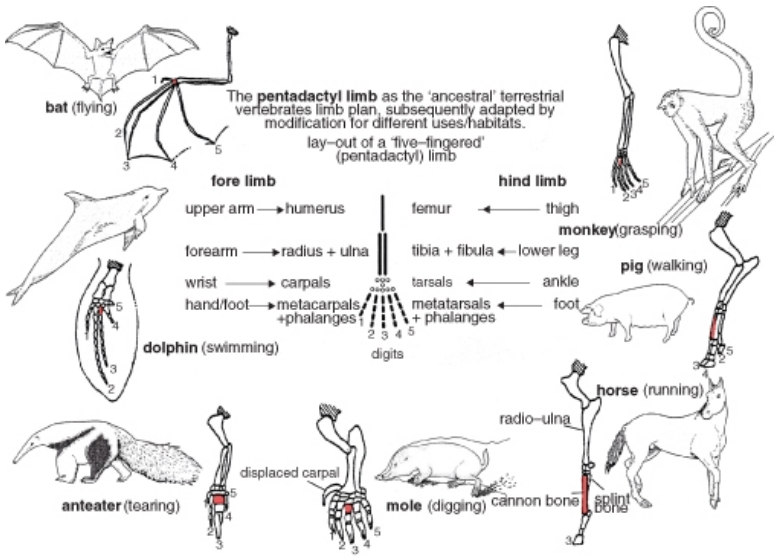

Figure 11.13: Forelimbs of mammals show adaptive radiation, or divergent evolution. Evolution has modified the original pattern in a common ancestor to suit a multitude of different environments.

In contrast to divergent evolution, whereby closely related species evolve different traits, **convergent evolution** involves distantly related species evolving similar traits. This pattern surfaces frequently in the history of life when different organisms occupy similar ecological niches. For example, three major groups of organisms have evolved wings for flight: reptiles (pterosaurs), birds, and mammals (bats), shown in **Figure** 11.14.

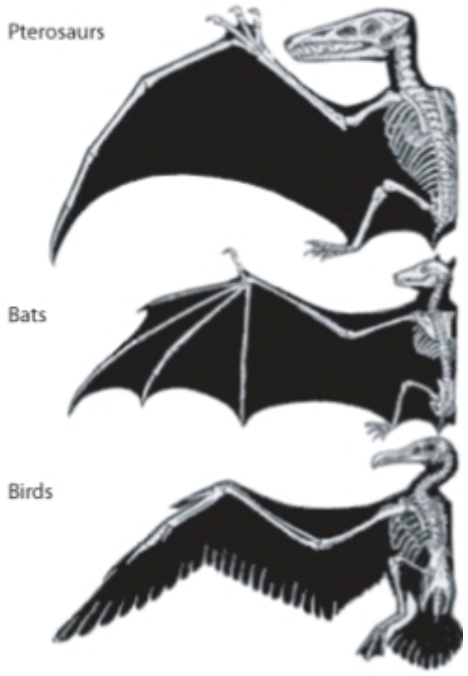

Figure 11.14: The wings of pterosaurs (1), bats (2) and birds (3) show convergent evolution. Similar structures adapt each group to flight, but each of the three types of wing evolved independently.

Australian fauna reveal both divergent and convergent patterns related to major geographical change, shown in **Figure** 11.15. Major groups of mammals evolved in the northern hemisphere and migrated to Australia across a land bridge. Later submerging of the land bridge isolated the Australian mammals, and the marsupials underwent their own adaptive radiation within their insular continent. Elsewhere, placental mammals evolved to out-compete the more primitive monotremes and marsupials, and underwent their own adaptive radiation. These independent radiations resulted in some wonderful examples of convergent evolution: An example: the marsupial Tasmanian wolf (now extinct) shared with the placental canines many adaptations to life as a hunting predator, shown in **Figure** 11.16.

One last, fascinating pattern within the history of life is **coevolution**. In coevolution, two species or groups of species influence each other's evolution and therefore evolve in tandem. Relationships may be positive for one species or both, or an evolutionary arms race between predator and prey. Flowering plants depend on insects for pollination, so have evolved colors, shapes, scents, and even food supplies which are attractive to certain

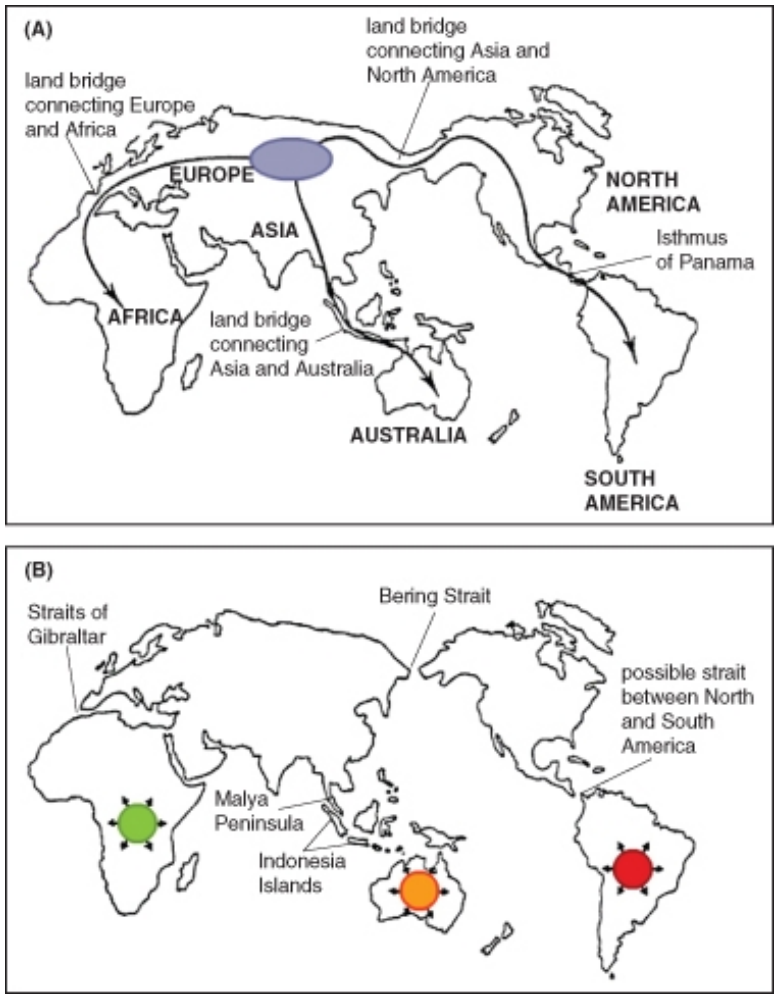

Figure 11.15: Australia's fauna demonstrates the importance of geography to evolution. Mammals evolved in the northern hemisphere and migrated to Australia across a land bridge (see A, above) which was later submerged (B). Marsupials persisted and underwent adaptive radiation in Australia. Elsewhere, the appearance of placental mammals spelled doom for the marsupials; placental mammals outcompeted them and underwent their own adaptive radiations. These separate radiations (green, orange, and red in B) resulted in a number of examples of convergent evolution.

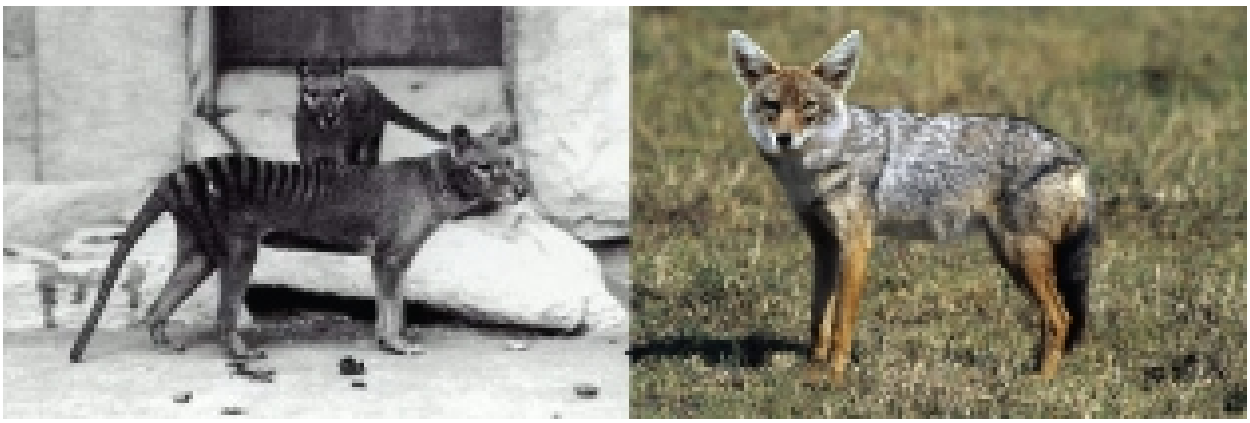

Figure 11.16: The thylacine or Tasmanian wolf, a marsupial, closely resembles the golden jackal, a placental canine; both show similar adaptations to predatory life, demonstrating convergent evolution. Marsupials and placentals evolved independently due to the loss of a land bridge connecting Australia to southeast Asia, so they provide examples of convergent evolution.

insect species. Insects, in turn, have evolved mouthparts, senses, and flight patterns which allow them to respond to and benefit from specific floral "offerings," shown in **Figure** 11.17. The **Endosymbiotic Theory** describes a special form of co-evolution: Mitochondria and chloroplasts evolve within eukaryote cells, yet because these organelles have their own DNA sequence, different from that of the nucleus in the "host" cell, organelle and host cell evolve in tandem – each influences the evolution of the other.

Figure 11.17: Impressive proboscis and vivid colors! Hawk moths and the zinneas influence each other's evolution, because the flower depends on the moth for pollination, and the moth feeds on the flower.

Closely related to coevolution is **coextinction**. If one member of a pair of interdependent species becomes extinct, the other is likely to follow. Famous examples were two species of bird lice which were obligate parasites on the passenger pigeon, shown in **Figure** 11.18.

When "Martha," a resident at the Cincinnati Zoo thought to be the last passenger pigeon in the world died on September 1, 1914, the extinction of the bird lice species followed. Alas, one louse species was later rediscovered on a band-tailed pigeon, and the other species had been misidentified.

Figure 11.18: The passenger pigeon and a parasitic species of louse (not the one pictured above) demonstrate coevolution and potential coextinction. Each species influenced the other's evolution, and when the host became extinct in 1914, the parasite narrowly escaped extinction only because an alternate host – the band-tailed pigeon – survived.

In this lesson, you have explored the tools we use to study the history of life, the Geologic Time Scale which organizes what we know, and a variety of patterns found in the 4.6 billion year story. In the next lessons, look for examples of these patterns as we follow that story from the origin of life to what is becoming known as the Sixth Extinction today.

Lesson Summary

- If the history of life is condensed into a single 24-hour "cosmological day," humans occupy only the last minute and one-half, and civilization, less than the final second.
- Fossils include mineralized remains of organisms, casts, impressions, footprints, burrows, droppings, eggs, or nests as well as frozen, dried, or amber-coated remains.
- The positions of fossils in rocks indicate their relative ages; older fossils and rock layers are deeper than fossils and rocks that are more recent.
- Radiometric dating measures the proportion of decay products of radioisotopes with known half-lives to estimate absolute age. Different isotopes with a range of half-lives cover the span of geologic time.
- Comparing DNA or protein in similar species can reveal evolutionary relationships and confirm patterns suggested by the fossil record.
- Geologic Time Scale divisions mark major events which highlight changes in climate, geography, atmosphere, and life.

- The largest units of time are Eons; the 4.6 billion years of earth's history are divided into four eons.
- The Phanerozoic includes the most recent 545 million years and the most detailed fossil record.
- Overall, the fossil record confirms Darwin's idea that life began as tiny single-celled bacteria and over time evolved to produce the complexity and diversity we celebrate today.
- Mass extinctions and episodic speciation interrupt an overall gradual increase in complexity and diversity.
- Evolution shows response to major environmental changes, including volcanism, continental drift, sustained warming and cooling, asteroid impact, and critical transformations of earth's atmosphere.
- The rate of evolution is not always uniform; gradualism does not characterize all speciation.
- The pattern of evolution is seldom linear, but rather more like a bush or family tree.
- Punctuated equilibrium, quantum evolution, and variable rates describe patterns of evolution which may differ from gradualism.
- In divergent evolution, also called adaptive radiation, closely related species evolve different traits to adapt to a variety of available niches.
- In convergent evolution, distantly related species evolve similar traits as adaptations to similar habitats.
- Geographic changes, including continental drift, affect patterns of evolution.

Review Questions

1. How do the conditions needed for fossilization explain the rarity of fossils?
2. Compare relative dating of fossils and rock layers to absolute dating.
3. Explain why "carbon dating" is an inadequate description of aging rocks and fossils.
4. Describe how molecular clocks clarify evolutionary relationships.
5. Compare and contrast Geologic Time with absolute time, including the limits of each.
6. Explain the ways in which the Geologic Time Scale and the fossils it records may be misleading concerning the history of life.
7. Construct a table or chart which shows five of the major patterns of macroevolution we have observed in the fossil record. Include the pattern name, a brief description or definition, causes or contributing factors (where applicable), and a specific example for each.
8. Explain how some of the patterns of evolution and environmental change account for worldwide differences in the distribution of mammals. Discuss placentals vs. marsupials.
9. Charles Darwin described an orchid from Madagascar that had a nectar well which measured 12 inches deep, keeping costly sugars far out of reach of all known butterflies and moths. He predicted the existence of a highly specialized pollinator moth with

a foot-long proboscis that could act as a straw to reach the nectar. After Darwin's death, scientists discovered a night-flying moth that matched Darwin's expectation and named it the "Predicta." Which pattern of evolution did Darwin see in the orchid? Explain why this is a good example of the pattern.

10. Relate human history to life's history, as shown in the Geologic Time Scale and fossil record.

Further Reading / Supplemental Links

- Colleen Whitney, Kate Barton, David Smith, "The Paleontology Portal." University of California Museum of Paleontology, Paleontological Society, Society of Vertebrate Paleontology, and US Geological Survey, 2003. Available on the web at:
- http://www.paleoportal.org/index.php
- "Continental Drift Animation." EduMedia-sciences, 2002-2007. Available on the web at
- http://www.edumedia-sciences.com/a95_l2-continental-drift.html
- Dave Smith, "Life Has a History – Level 2." University of California Museum of Paleontology, 7/18/06. Available on the web at:
- http://www.ucmp.berkeley.edu/education/explorations/tours/intro/Intro5to12/tour1nav.php
- Jim Kurpius. Rob Guralnick, Jennifer Johnson, Anne Monk,Judy Scotchmoor, and Mark Stefanski, "Understanding Geologic Time." University of California Museum of Paleontology, 1994-2007. Available on the web at:
- http://www.ucmp.berkeley.edu/education/explorations/tours/geotime/index.html
- Lexi Krock, "The Missing Link: A Brief History of Life." Nova Online, last updated February 2002. Available on the web at:
- http://www.pbs.org/wgbh/nova/link/history.html
- Roy Caldwell and David R. Lindberg, "Evolution 101." University of California Museum of Paleontology, 2007. Available on the web at:
- http://evolution.berkeley.edu/evolibrary/article/evo_01

Vocabulary

absolute aging Measures half-lives of radioactive isotopes to calculate the number of years which have elapsed since a rock formed; also known as absolute dating.

adaptive radiation A pattern of speciation which involves the relatively rapid evolution from a single species to several species to fill a diversity of available ecological niches.

coevolution Evolution in which two species or groups of species influence each other's evolution and therefore evolve in tandem.

coextinction If one member of a pair of interdependent species becomes extinct, the other is likely to become extinct as well.

convergent evolution Evolution whereby distantly related species evolving similar traits.

divergent evolution Evolution whereby closely related species evolve different traits.

eons The largest units of time within the Geologic Time Scale; divided into eras, which are also divided into periods, epochs, and stages.

episodic speciation A pattern of periodic increase in new species; follows mass extinctions as well following major new "discoveries" or "ideas" – for example, the biochemical pathways for photosynthesis or cellular respiration.

extinction The death of an entire species.

fossils The preserved remains or traces of organisms; provide extremely rare but vivid windows to the past.

Geologic Time Scale A column of rock layers which reflects the history of sedimentary rock formation and changing life.

gradualism The idea that evolution progresses via slow, steady, gradual change; suggests that changes accumulate continuously as one species evolves to become another.

index fossils Widespread, short lived fossils that can be used to help identify rock layers of the same age spread around the Earth, providing the relative age of other fossils.

macroevolution Evolution at or above the species level.

microevolution Describes changes within a species or population.

molecular clocks Measure changes in DNA or proteins to indicate degrees of relationship among species.

paleontologists Scientists who study fossils.

punctuated equilibrium Proposes that species remain the same for long periods, and that change occurs infrequently but rather rapidly under unusual conditions such as geographic isolation or migration.

quantum evolution Proposes that the origins of major groups (families, orders, and classes) occurred as a response to drastic changes in environment or adaptive zones.

trace fossils Fossils consisting of footprints, burrows, droppings, eggs, nests, and other types of impressions.

Points to Consider

- Consider the range of tools used to study a history which no human could witness. These range from fossils – the actual remnants of living organisms – to comparisons of molecules within organisms still living today. Which tools do you consider most reliable? Does the fact that the information from one set of tools often confirms that evidence collected using a different set of tools strengthen your acceptance of the data?
- Review the various patterns of macroevolution, from mass extinction to coevolution and coextinction. Which of these best support the depiction of evolution as a bush, rather than an arrow? Which support the idea that evolution builds on what already exists, so the more variety there is, the more there can be in the future?

11.2 Lesson 11.2: Early Life

Lesson Objectives

- Relate the nature of science to our current understanding of the origin of life.
- Describe the formation of the atoms which build the Earth and its life.
- Explain the formation of the moon, and its effects on Earth's conditions for life.
- Compare and contrast Earth's early atmosphere with today's atmosphere.
- Discuss the formation of Earth's early atmosphere and oceans.
- Indicate the age of the Earth and identify supporting evidence.
- Interpret the importance of Miller and Urey's experiment.
- Relate the properties of phospholipids to the formation of the first membranes.
- Compare and contrast the "genes-first" model of the origin of life to the "metabolism first" model.
- Explain why some scientists believe that RNA was the basis of early life.
- Evaluate the hypothesis that exogenesis explains the origin of life on Earth.
- Describe the theoretical characteristics of the first cell.
- Discuss the concept of a "LUCA," or last universal common ancestor.
- Indicate the origin of photosynthesis and its consequences for Earth's life and atmosphere.
- Analyze the effects of the development of atmospheric oxygen on life.
- Explain the importance of the emergence of cellular respiration.
- Explain the Endosymbiotic Theory of the origin of eukaryotic cells.

- Evaluate the evidence for the Endosymbiotic Theory.
- Identify the origins of the three major domains of life.
- Analyze the evolutionary potential of the eukaryotic cell.
- Discuss the pros and cons of the evolutionary "tree" as a way of depicting the evolutionary process.

Introduction

No part of the story of life holds more mystery or fascination than its ultimate origins. Cosmologists, geologists, paleontologists, and biologists have collected, compared, scrutinized, evaluated, and revised many kinds of evidence in order to see into the past. As a result, well-accepted theories now illuminate nearly 4 billion years of life's history, 4.6 billion years of Earth's history, and even 13.7 billion years back to the **Big Bang**, which began the universe as we know it. Yet until the 19^{th} century, most people believed the Earth was just 6,000 years old. We still do not know whether life exists beyond our Earth, nor can we predict where evolution will take life on Earth in the future, and our theories leave many chapters of the story untold. As you explore the early history of life, you must remember that the nature of science is to continue to question its own conclusions, to persist in seeking new information, and to readily modify or even overturn long-accepted theories, if new evidence contradicts them. This lesson includes some of the best explanations science can currently provide for life's origin and early evolution. A story of stardust, explosions, collisions, competition, and cooperation should not disappoint you, but it probably won't give you all the answers you seek. If this lesson provides insight and raises more questions, you will have a firm foundation upon which to build future understanding as it unfolds. Perhaps you could join the search!

Formation of Earth: We are Made of Stardust!

We will begin our story of the origin of life by exploring the origin of the materials which build it. The materials have a beauty and diversity of their own; perhaps your study of the Periodic Table of the Elements gave you an appreciation for their variety and individuality. Earth began as the solar system began – often described as a giant rotating cloud of dust, rocks, and gas. "Dust, rocks, and gas" may not sound inspiring, but this cloud contained the 92 elements or kinds of atoms which somehow combine to form every corner – living and nonliving - of the exquisite world we inhabit. The Big Bang (9 billion years earlier!) produced the atoms of hydrogen and helium. Elements as heavy as lithium followed the Big Bang within minutes. Stars such as red giants fused hydrogen and helium nuclei to form elements from carbon (the foundation of life!) to calcium (now our bones and teeth). Supernova explosions formed and ejected heavier elements such as iron (for red blood cells). We are not just "dust." We - and our world - are stardust!

How did this rotating cloud of stardust become our solar system? One theory suggests

that a nearby supernova sent a shock wave through the cloud, increasing its spin to form a protoplanetary disk, shown in **Figure** 11.19. Most of the mass concentrated in the middle and began to heat up, but large debris and collisions resulted in concentrations of matter outside the center. Eventually, heat in the central core began nuclear fusion of hydrogen to helium, and the Sun ignited. Matter outside the Sun's gravity separated into rings of debris, and collisions of objects within the rings formed larger objects, which eventually became the planets. Solar wind cleared much of the remaining non-planetary material from the disk.

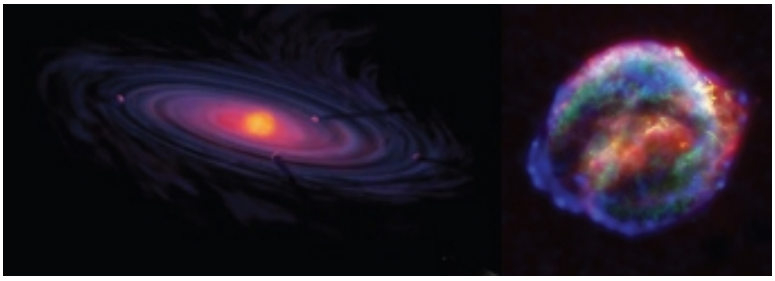

Figure 11.19: At left is an artist's conception of the protoplanetary disk, which eventually formed our solar system. At right is an X-ray image of the remnant of Kepler's Supernova, SN 1604, constructed of images from NASA telescopes and observatories. Together, art and science suggest the beauty of the "dust, gas, and rocks" which gave birth to our earth and its life.

One of the collections of debris, approximately 150 million kilometers from the Sun, was the protoplanet Earth. Newborn, Earth was very different from the home we know today. Bombarded by debris and heated by radioactive decay and the pressure of contraction, the Earth at first was molten. Heavy elements sank to the center, and lighter ones surfaced. Heat and solar wind meant that no atmosphere and no oceans were present.

Eventually, contraction and cooling allowed formation of a crust and retention of an atmosphere. However, continued bombardment melted portions of the crust for long periods. About 4.5 billion years ago, Earth collided with another protoplanet, Theia. This "big whack" gave us our moon and tilted Earth on its current axis, leading to the seasons, which now influence so much of life's diversity. The Big Whack may also have initiated plate tectonic activity by speeding up the Earth's rotation. Since then, however, the moon's tidal drag may be slowing that rotation; scientists suggest that the day/night cycle during the Hadean may have been as short as 10 hours.

As the Earth continued to cool amidst heavy bombardment, steam escaped from the crust and active volcanoes released other gases to form a primitive atmosphere, which contained ammonia, methane, water vapor, carbon dioxide, and nitrogen, but no more than a trace of oxygen. In the absence of oxygen, no ozone layer protected Earth from the Sun's ultraviolet rays. Between 4.2 and 3.8 billion years ago, clouds and rain formed the oceans. The oceans were olive green, and the reddish atmosphere would have been toxic to modern multicellular organisms. Yet the stage was set for life to begin.

First Organic Molecules: Hypotheses About the Origin of Life's Chemistry

The Hadean Eon ended 3.8 billion years ago, its timeline marked by Earth's oldest known rocks (between 3.8 and 4.2 billion years old) and oldest known minerals (formed 4.4 billion years ago). Scientists use these dates to estimate that the Earth itself is 4.6 billion years old. Evidence for life during the Hadean does not exist, although many scientists push the theoretical origin back that far. How – and when – did life arise?

Once again, we will begin with the materials of life – this time, **organic molecules,** made primarily of the element carbon. Most scientists agree that these organic molecules arose before cells, which we now consider essential to the definition of life. Several hypotheses and experiments suggest ways in which organic building blocks may have formed.

In 1924, Aleksandr Oparin proposed that life could have developed through gradual chemical evolution in a "**primordial soup**." In 1953, Stanley Miller and Harold Urey designed a now-famous test of the hypothesis that the conditions of primitive Earth favored chemical reactions that synthesized organic molecules from inorganic precursors. Their experiment (**Figure** 11.20) showed that a mixture of gases, believed to be part of the primitive Earth atmosphere, when subjected to sparks representing lightning, formed a mixture of monomers representing each of the four major groups of organic molecules. Although DNA, RNA, and polymers were absent, 13 of the 22 amino acids that make up modern protein, plus lipids, sugars, and some building blocks of DNA and RNA, were among the products of the experiment.

The "leap" from building blocks to polymers and from organic soup to individual replicating units has been more difficult to demonstrate. In the '50s and '60s, Sydney Fox showed that early Earth conditions could result in short chains of amino acids, which in turn could form enclosed spheres. Phospholipids can self-organize into membranes in a similar fashion, and cell membranes today consist primarily of a bi-layer of these lipids. Phospholipids or polypeptides could have surrounded and protected early metabolic units, forming **protocells** shown in **Figure** 11.21, simple membrane-enclosed spaces which may have led to the later evolution of true cells.

Walter Gilbert, Carl Woese, and Alexander Rich proposed that RNA, because it can serve both catalytic and replicating functions, was the first informational molecule, and formed the "**RNA World Hypothesis**" for the origin of life. Sol Spiegelman created a short chain of RNA which was able to replicate itself in the presence of RNA polymerase; the segment is now known as the "Spiegelman monster." The idea that a successful replicator molecule preceded the evolution of biochemical pathways is the "**Genes-First**" model.

In contrast, Günter Wächtershäuser proposed that sulfides of iron and other minerals contain energy which could have polymerized basic building blocks. He argued that extensive evolution of biochemical pathways might have preceded replicator molecules and individualization of life. His ideas formed the basis of William Martin and Michael Russell's 2002

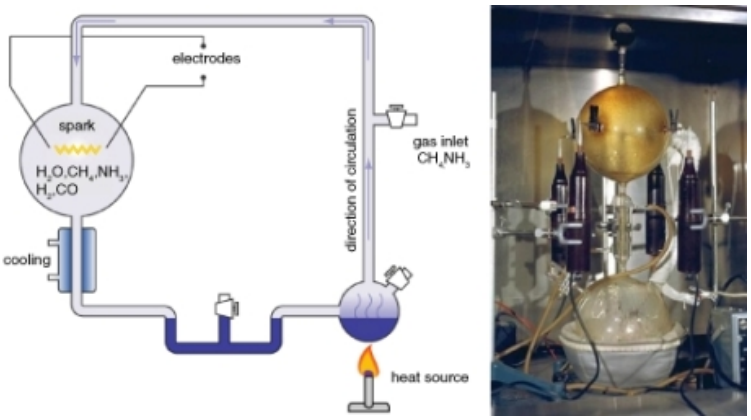

Figure 11.20: The Miller-Urey experiment subjected a mixture of gases thought to be present in Earth's primitive atmosphere to sparking, representing lightning. After one week, the nonliving system had formed 13 of the 22 amino acids which make up modern proteins, sugars, lipids, and some of the building blocks of DNA and RNA.

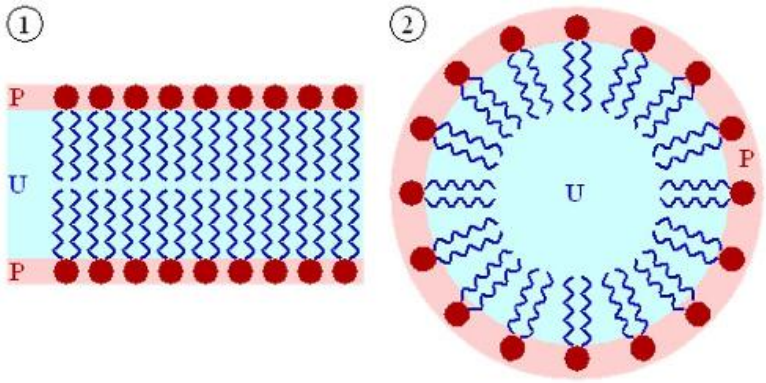

Figure 11.21: Phospholipids, with hydrophilic phosphate "heads" (P) and hydrophobic lipid "tails" (L) self-assemble into membranes (1) and enclosing spheres (2) which could have protected early metabolism from "outside" chemical disturbances.

hypothesis that black smokers at seafloor spreading zones, shown in **Figure** 11.22, could have provided conditions for extensive chemical and biochemical pathway evolution. Their reasoning suggests that lipid membranes allowing independent lives away from the smokers could have been a last step in early evolution. The fact that archaebacteria and eubacteria (and us eukaryotes!) have completely different membrane lipids but similar metabolism supports the concept of early biochemical pathway evolution. These ideas comprise the "**Metabolism-First**" model.

The discovery of organic molecules in space supports the **exogenesis** hypotheses which propose that life could have originated elsewhere – on Mars, or at some distant point in the universe. Comets and meteorites are known to contain organic molecules, and could have delivered them to Earth. Exogenesis does not really answer the question of how life originated, but provides a much wider temporal and spatial framework in which it could have happened.

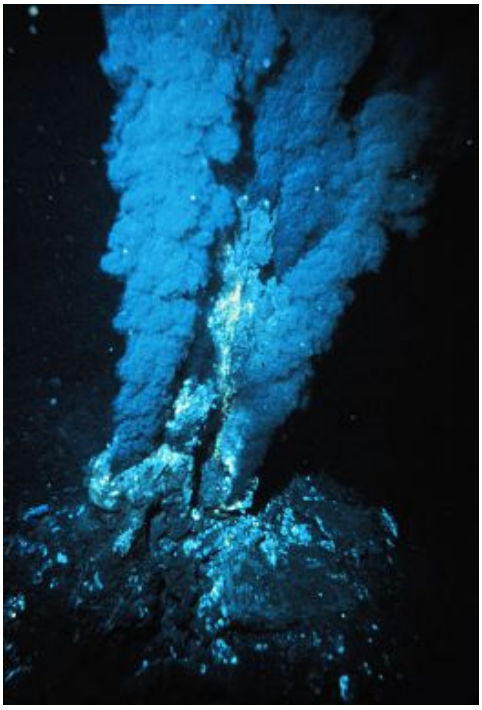

Figure 11.22: Black smokers at a mid-ocean ridge hydrothermal vents could have provided conditions suitable for the evolution of early biochemical pathways and much of metabolism, even before lipid membranes formed cells. Martin and Russell propose that the last universal common ancestor may have emerged from a black smoker.

Emergence of Life: The First Cells were Prokaryotes

Although many hypotheses and some experiments and observations explore the origin of cellular life, actual events remain unknown. If earth's life first arose on earth, rather than by exogenesis, its timing is speculative, for no fossils record that event. Admitting that many conflicting hypotheses exist, we often express our current understanding of the story this way:

Perhaps four billion years ago during the Hadean Eon, lightning and a primitive atmosphere produced an organic soup of chemicals. As the "soup" became more concentrated, molecules began to interact with one another. As molecules became more complex, some molecules helped to speed up or catalyze chemical reactions (perhaps RNA, but eventually protein). Within that highly reactive soup, a molecule gained the ability to copy itself, becoming the first replicator (perhaps RNA, but eventually DNA). Copies contained errors, and errors which prevented replication caused the copies to "die out." Copies that replicated faster survived to make more copies. Eventually, lipid membranes surrounded some of these chemicals, protecting them from reacting with other chemicals.

Although many protocell "species" probably populated the early "soup," scientists believe that only one – a last universal common ancestor (**LUCA**) – emerged about 3.5 billion years ago during the Archean Eon, and later gave rise to all cellular life on earth. This **prokaryote** probably had a cell membrane and ribosomes, and used DNA for information storage, RNA for information transfer, and protein for catalyzing chemical reactions – like all life today. The first cells were probably **heterotrophs**, feeding on energy-rich chemicals concentrated in the "soup." Alternatively, they could have been **chemoautotrophs**, extracting energy from inorganic molecules. Not long after prokaryotic cells emerged, they split into two major groups, Eubacteria and Archaebacteria. Both persist today, although Archaebacteria more often inhabit extreme habitats.

Inevitably, a diminishing supply of food molecules led to competition. At some point, **glycolysis** evolved as a pathway for transferring energy from organic molecules to ATP. This pathway persists in almost all organisms today.

Eventually, about three billion years ago, a new strategy evolved among some prokaryotes, which used sunlight to make carbohydrates from carbon dioxide and water. **Photosynthesis** provided a new source of food molecules for both autotrophs and the heterotrophs that "learned" to consume them. The oldest fossils, stromatolites, (**Figure** 11.23) record abundant photosynthetic cyanobacteria from that time.

Oxygen produced by photosynthesis first oxidized iron dissolved in the oceans, creating massive deposits of iron ore. Eventually, toward the end of the Archean, oxygen began to accumulate in the atmosphere, creating a major environmental change that is sometimes called the "**Oxygen Catastrophe**." Oxygen was indeed toxic to many of the prokaryotes which had evolved as **anaerobes**. However, ultraviolet rays converted some of the oxygen to ozone, which prevented much of that harmful radiation from reaching the earth's surface.

Figure 11.23: Stromatolites are microbial mats made by some of the earliest photosynthetic organisms on Earth. Fossil stromatolites (left) are among the oldest fossils on Earth, although some have been interpreted to be of abiotic origin. Living stromatolites (right), mats of cyanobacteria, are found primarily in hypersaline lakes and marine lagoons.

Thus, while an oxygen atmosphere may have killed many species, it allowed survivors to colonize previously uninhabitable ocean surface and terrestrial habitats. Even more important to the future of life, some prokaryote survivors "learned" how to use oxygen to harvest a great deal more energy from organic molecules. The energy efficiency of **aerobic respiration** paved the way for the emergence of larger and more complex organisms in the Proterozoic Eon.

Eukaryotes: Alliance, Invasion, or Slavery?

You have learned that our own **eukaryotic** cells protect DNA in chromosomes with a nuclear membrane, make ATP with mitochondria, move with flagella (in the case of sperm cells), and feed on cells which make our food with chloroplasts. All multicellular organisms and the unicellular Protists share this cellular intricacy. Bacterial (prokaryotic) cells are orders of magnitude smaller and have none of this complexity. What quantum leap in evolution created this vast chasm of difference?

The widely accepted **Endosymbiotic Theory**, shown in **Figure** 11.24, proposes that many organelles were once independently living cells. Larger cells engulfed these smaller cells but did not digest them, perhaps due to prey defenses. Alternatively, perhaps the smaller cells invaded the larger cells with the "intent" to parasitize. In either case, with their own DNA, the endosymbionts reproduced independently within the cell, and cell division passed them on to future generations of cells. Aerobic bacterial invaders would have been able to use oxygen to further break down and use energy from the host's "wastes" from glycolysis. So much energy (ATP) resulted that some was available to the host; a mutually beneficial symbiosis resulted. This intriguing story of cooperation – so different from natural selection's emphasis on competition – explains the origin of our mitochondria. A similar tale is told for chloroplasts; the benefit for a heterotrophic "host" is clear. Some scientists view cilia, flagella, peroxisomes, and even the cell nucleus as endosymbionts, but these ideas are less widely accepted.

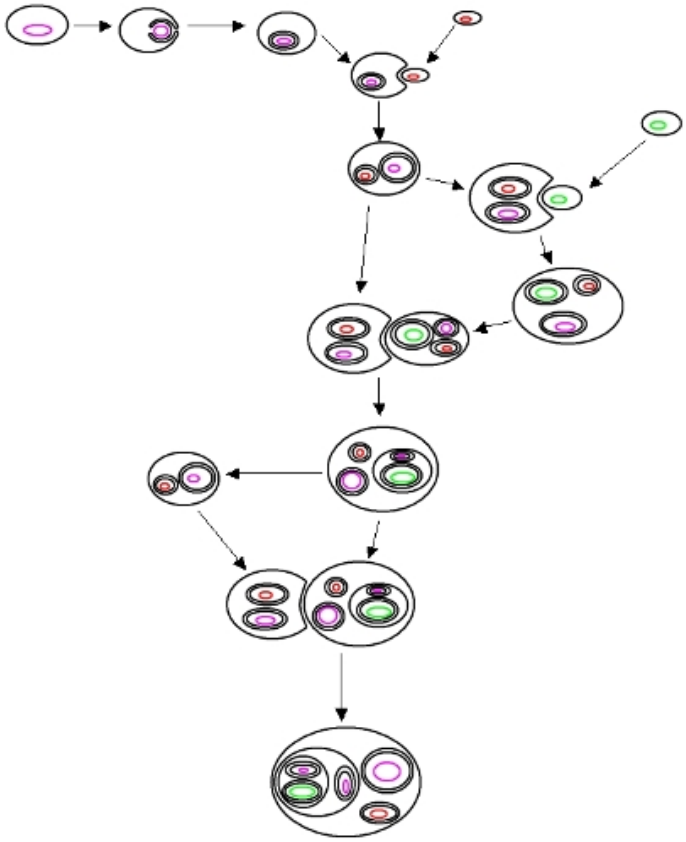

Figure 11.24: The Endosymbiotic Theory holds that eukaryotic cells arose when larger prokaryotic cells engulfed smaller, specialized prokaryotes, without later digestion. The smaller cells reproduce independently within the larger cells, to the potential benefit of both. The diagram shows possible events leading to endosymbiosis. Black: membrane; Pink: eukaryotic DNA; Green: cyanobacteria/chloroplast DNA; Red: proteobacteria/mitochondrial DNA

What is the evidence for this maverick evolutionary pathway? Biochemistry and electron microscopy provide convincing support for the Endosymbiotic Theory. The mitochondria and chloroplasts which live within our eukaryotic cells share the following features with prokaryotic cells:

- Organelle DNA is short and circular – and sequences do not match DNA in the nucleus.
- Molecules that make up organelle membranes resemble those in prokaryotic membranes – and differ from those in eukaryotic membranes.
- Ribosomes in these organelles are similar to those of bacteria – and different from eukaryotic ribosomes.
- Reproduction is by binary fission – not mitosis.
- Biochemical pathways and structure show closer relationships to prokaryotes.
- Two or more membranes surround these organelles.

The "host" cell membrane and biochemistry are more similar to those of Archaebacteria, so scientists believe eukaryotes descended more directly from that major group (**Figure** 11.25). However, the standard evolutionary tree cannot accurately depict our ancestry, because the origin of the eukaryotes combines traditional descent from the Archaea with landmark cohabitation alliances forged with the Bacteria.

The timing of this dramatic evolutionary event (more likely a series of events) is not clear. The oldest fossil clearly related to modern eukaryotes is a red alga dating back to 1.2 billion years ago. However, many scientists place the appearance of eukaryotic cells at about 2 billion years. Some time within Proterozoic Eon, then, all three major groups of life – Bacteria, Archaea, and Eukaryotes – became well established. Geologists hypothesize the oldest supercontinent, Columbia, between 1.8 and 1.5 years ago, as the backdrop for the further evolution of these three domains.

Eukaryotic cells, made possible by endosymbiosis, were powerful and efficient. That power and efficiency gave them the potential to evolve new ideas: multicellularity, cell specialization, and large size. They were the key to the spectacular diversity of animals, plants, and fungi which populate our world today. We will tell their much more familiar story in the next lesson. Nevertheless, as we close the history of early life, reflect once more on the remarkable but often unsung patterns and processes of early evolution. Our "size-ism" sets us up to wonder at plants and animals, and ignore bacteria. Our human senses cannot directly perceive the unimaginable variety of single cells, the architecture of organic molecules, or the intricacy of biochemical pathways. Let your study of early evolution give you a new perspective – a window into the beauty and diversity of unseen worlds – now and throughout Earth's history. Apart from the innumerable mitochondria which call your 100 trillion cells home, your body contains more bacterial cells than human cells. You, mitochondria, and your resident bacteria share common ancestry – a continuous history of the gift of life.

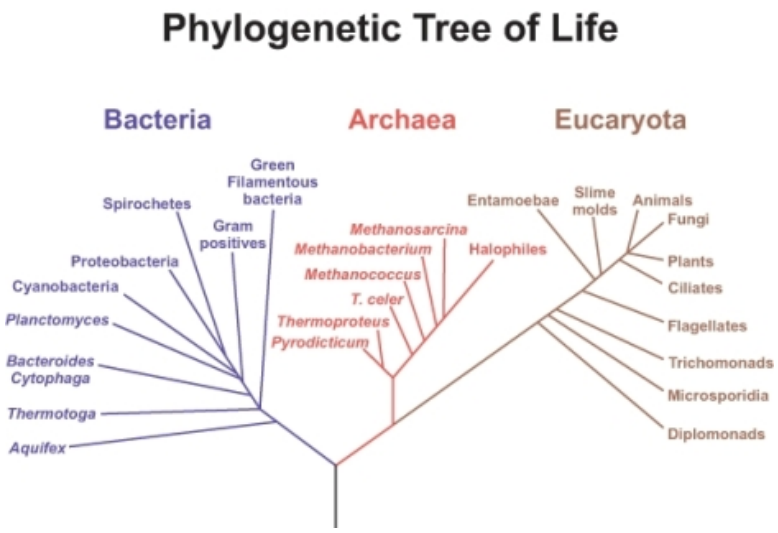

Figure 11.25: The three major domains of life had evolved by 1.5 billion years ago. Biochemical similarities show that we Eukaryotes share more recent common ancestors with the Archaea, but our organelles probably descended from Bacteria by Endosymbiosis.

Lesson Summary

- The Big Bang and stars such as red giants made the atoms which build life.
- Earth gradually condensed into a molten protoplanet, constantly bombarded with debris.
- Steam escaping from the formative crust and volcanic gases contributed to Earth's early atmosphere, which probably contained methane, ammonia, carbon dioxide, water and nitrogen. Such an atmosphere would be toxic to most modern organisms.
- No oxygen meant no ozone; ultraviolet radiation reached the Earth and threatened life with deadly, mutating rays.
- Eventually, water in the atmosphere condensed into clouds and rain, forming oceans.
- Earth's oldest known rocks are between 3.8 and 4.2 billion years old. The oldest minerals are 4.4 billion years old. Scientists estimate that the age of the Earth is 4.6 billion years.
- Miller and Urey showed that a spark igniting a mixture of gases resembling Earth's primitive atmosphere could produce most of the building block organic molecules of life – forming an "organic soup."
- Some lipids and certain polypeptides can spontaneously form into protocells; early membranes could have self-organized in this way.
- The "Genes-first" hypothesis proposes that replicating molecules evolved before biochemical pathways.
- Some scientists believe RNA, rather than DNA, was the first replicator.
- The "metabolism-first" model suggests that biochemical pathways evolved in an or-

ganic soup before self-replicating molecules.
- Many scientists accept that a "last universal common ancestor" (LUCA) cell arose from the primeval soup of organic molecules.
- This prokaryote probably had a cell membrane and ribosomes, and used DNA for information storage, RNA for information transfer, and protein for catalyzing chemical reactions – like all life today.
- The first cells were probably heterotrophs feeding on organic soup, or chemoautotrophs using the energy in inorganic molecules.
- Not long after the LUCA prokaryote arose, life split into two groups, Bacteria and the Archaebacteria.
- Photosynthesis arose roughly 3 billion years ago.
- The oldest fossils, stromatolites, preserve photosynthetic cyanobacteria.
- Oxygen produced by photosynthesis eventually changed Earth's atmosphere.
- Ozone formed, protecting life from damaging UV radiation.
- The widely accepted Endosymbiotic Theory explains the origin of eukaryotic cells as a merging of several kinds of prokaryotic cells.

Review Questions

1. Why is understanding the nature of science important to studying the origin of life on Earth?
2. Interpret the statement "we are made of stardust."
3. Describe the effects of the moon on the conditions for life on Earth, according to the impact theory of the moon's origin.
4. Discuss the formation of Earth's atmosphere and compare it to today's.
5. Identify the age of the Earth, and give the supporting evidence.
6. Describe Miller and Urey's experiment, and evaluate its importance to our understanding of the origin of life.
7. Compare and contrast the RNA World, genes first, metabolism first, and exogenesis models of the origin of life. Evaluate the evidence supporting each model.
8. List the characteristics scientists attribute to "last universal common ancestor" of life on Earth.
9. Indicate when scientists believe photosynthesis originated, and what evidence suggests this. Analyze the effects of the origin of photosynthesis on life existing at that time.
10. Analyze the theory which explains our current understanding of the origin of eukaryotic cells. In what way does it differ significantly from "traditional" ideas of evolution?

Further Reading / Supplemental Links

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Vocabulary

endosymbiotic theory Theory which proposes that many organelles were once independently living cells; describes the formation of eukaryotic cells.

genes-first model The idea that a successful replicator molecule preceded the evolution of biochemical pathways.

LUCA The last universal common ancestor; the first true cell, which formed about 3.5 billion years ago.

metabolism-first model The proposal that extensive evolution of biochemical pathways might have preceded replicator molecules and individualization of life.

organic molecules The "materials of life" - molecules made primarily of the element carbon.

oxygen catastrophe Toward the end of the Archean, oxygen began to accumulate in the atmosphere, killing many anaerobic species.

primeval soup Oceans in which gradual chemical evolution formed life; proposed by Aleksandr Oparin.

protocells Simple, membrane enclosed early metabolic units surrounded by phospholipids or polypeptides; precursors to true cells.

RNA world hypothesis Hypothesis that proposes that RNA evolved prior to DNA.

Points to Consider

- Which theory of life's origins do you consider most plausible: genes first, metabolism first, or exogenesis? What kinds of evidence would be required to support each theory?
- The standard form for an evolutionary tree is a series of branching lines which show common ancestors. Can you imagine a format which could show Endosymbiosis, as well as common ancestry?

11.3 Lesson 11.3: Multicellular Life

Lesson Objectives

- Assess the impact of global environmental changes on the evolution of life.
- Describe the diversity of unicellular organisms which arose over 2 billion years of evolution.
- Evaluate the importance of major evolutionary developments which preceded the Cambrian explosion: colony formation, cell specialization, and sexual reproduction.
- Evaluate the importance of some factors which contributed to the "Cambrian explosion" of biodiversity.
- Trace the evolution of plants and animals from aquatic to terrestrial habitats.
- Connect changes in atmospheric O_2 and CO_2, temperature, geography, and sea level to extinctions and radiations of various groups throughout the Paleozoic.
- Identify recurrent extinctions as losses of diversity, but also opportunities for the evolution of new species.
- Describe the conditions under which the dinosaurs emerged to dominate life on Earth.

- Identify the diversity of habitats and niches occupied by the dinosaurs during their "golden age."
- Discuss the relationships between reptiles, birds and mammals during the age of the dinosaurs.
- Explain the coevolution of flowering plants and insects during the Cretaceous.
- Evaluate the evidence for an "impact event" as the primary cause of the K-T extinction which ended the reign of the dinosaurs.
- Analyze the emergence of mammals and birds as the dominant land animals during the early years of the Cenozoic.
- Connect sea level, land bridges, and climate to their effects on evolution.
- Explain the connection between CO_2 levels, temperature, and glaciation.
- Discuss the factors which contribute to the "sixth" major extinction.

Introduction

Biologists estimate that 99% of the species which have ever lived on Earth are now extinct, and up to 80 million species populate our world today. It is the great diversity of species that allows at least some organisms to survive major changes in the environment.

4 billion years of simple, prokaryotic cells

3 billion years of photosynthesis

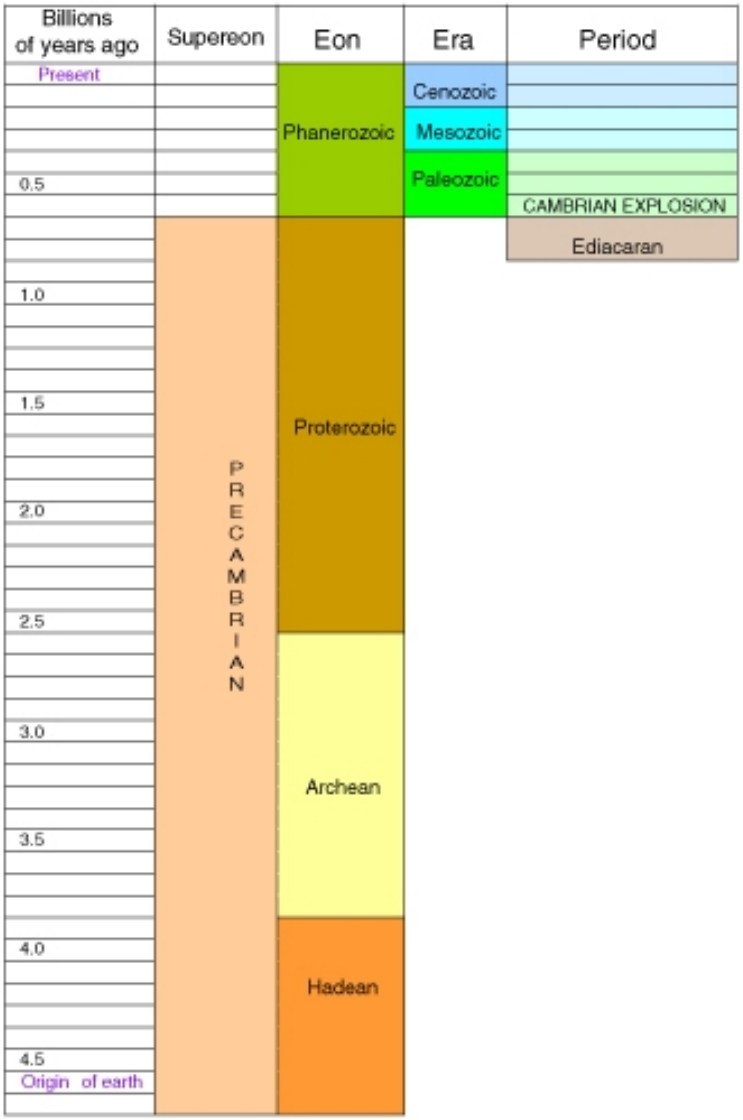
2 billion years of complex, eukaryotic (but still single!) cells

1 billion years of multicellular life

The history of life reaches the last billion years of Earth's 4.6 billion-year history with no hint of the wondrous diversity of life as humans know it. Not until nearly 80% of Earth's history had passed did multicellular life evolve. The fossil record tells the story: millions of species of fish, amphibians, reptiles, birds, mammals, mosses, ferns, conifers, flowering plants, and fungi populated the seas and covered the Earth - as continents crashed together and broke apart, glaciers advanced and retreated, and meteors struck, causing massive extinctions. Life has had a colorful and exciting last billion years, spawning diversity almost beyond our comprehension.

And yet, the giant steps of evolution remain back in the Precambrian. Its catalog of evolutionary innovations is long and impressive:

- Energized elements from stardust formed simple organic molecules.
- Building blocks chained together to form catalysts and self-replicating macromolecules.
- Biochemical pathways evolved.
- Protective yet permeable membranes enclosed the catalysts, replicators and their metabolic retinue.
- Early prokaryotic cells "learned" to make ATP by splitting glucose.


Billions of years ago
Supereon
Eon
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Phanerozoic
Cenozoic
Mesozoic
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0.5
CAMBRIAN EXPLOSION
Ediacaran
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Proterozoic
PRECAMBRIAN
2.0
2.5
3.0
Archean
3.5
4.0
Hadean
4.5
Origin of earth

Figure 11.26

- Others began to harvest sunlight energy through photosynthesis.
- Photosynthetic cyanobacteria produced vast amounts of "waste" oxygen, dramatically altering the Earth's atmosphere.
- The oceans rusted (iron ore deposits).
- An ozone layer formed, shielding life from UV radiation.
- The "O_2 catastrophe" killed many anaerobic prokaryotes.
- Still other prokaryotes "learned" to use the new O_2 to release the energy remaining in carbohydrates products of glycolysis.
- Endosymbiosis created eukaryotes, firmly establishing the three major evolutionary lineages, which yet today comprise the living world.

The timing and exact nature of most of these innovations is speculative; indeed, the first few may have been extraterrestrial and even deeper in time. They comprise perhaps the most important landmarks in the evolution of life, but the fossil record is sketchy due to prokaryote size, rock layer metamorphosis, and burial by more recent rocks.

Overall, we know remarkably little about Precambrian life. The **Cambrian Period** documents the greatest flowering of life of all time, and gives its name - in a rather negative sense - to the 4 billion years of Earth history that preceded it. Before we dive into the famous Cambrian "explosion," we will look more carefully at the last Eon of the Precambrian, which set the stage for this most famous burst of evolution.

Late Precambrian: Setting the Stage for an Explosion of Biodiversity

The geologic record of the Proterozoic, the most recent eon of the Precambrian, is much better than that of the Archean and Hadean Eons before it. Accordingly, we know that **supercontinents** formed by collision and broke apart by rifting. The atmosphere changed dramatically with the addition of oxygen and a protective ozone layer. Glaciations covered much of the Earth with ice so extensively that it is known as the **"Snowball Earth"** during that period (**Figure** 11.27). Eventually, enough CO_2 escaped from volcanoes to begin a period of global warming; melting opened a great variety of new niches. The severe restriction and subsequent opening of opportunities may have driven the later Cambrian explosion.

Within this dramatic environmental panorama, the three major lineages of life – Bacteria, Archaea, and Eukaryotes continued to diversify. Plant, animal, and fungal ancestors diverged as solitary cells. Gradually, some of these cells began to live in colonies. Within the colonies, primitive **specialization** among cells made certain tasks more efficient. The modern green alga, *Volvox* illustrates a comparable level of organization (**Figure** 11.28). The line between colonies and multicellular organisms is difficult to draw, but most scientists agree that true plants had evolved by about 1 billion years ago, and animals evolved about 100 million years later.

Figure 11.27: The geologic record documents at least two ice ages during the last eon of the Precambrian. One was so severe that some scientists believe ice then covered the entire globe, and they dub it the "Snowball Earth." The icy constriction of life and later meltdown opening of niches may have contributed to the explosive evolution of the Ediacaran and Cambrian Periods that followed.

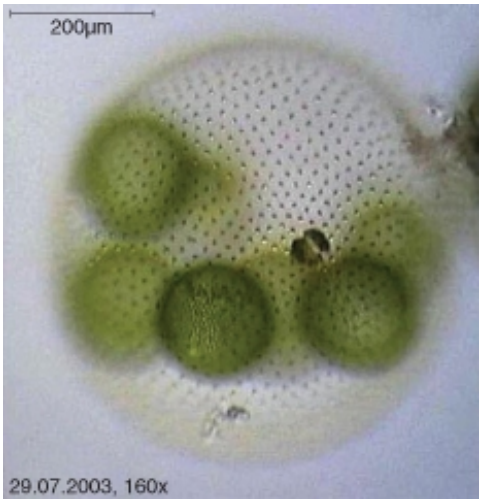

Figure 11.28: The green alga shows the multicellularity and early cell specialization which probably characterized early colonial eukaryotes. Specializations include anterior sensory cells, asexual and two types of sexual reproductive cells, and coordination among flagellate cells.

The fossil record shows that some eukaryotes had begun to reproduce sexually by a little over a billion years ago (**Figure** 11.29). **Sexual reproduction** was a major evolutionary innovation, producing more variety among offspring and thus more rapid adaptation to changing environments.

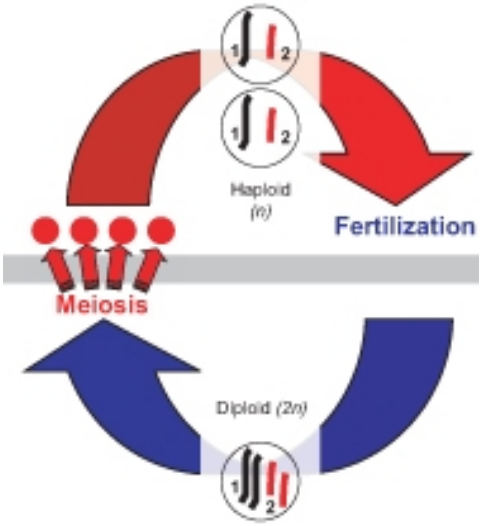

Figure 11.29: The evolution of sexual reproduction around 1 billion years ago increased variety among offspring, and may have increased rates of evolution (see chapter).

Near the end of the Precambrian - not until just over 600 million years ago, a unique assemblage of multicellular organisms left a fossil record which gives us our first glimpse of multicellular diversity – the **Ediacaran biota** (the name is taken from the hills in Australia where the first such fossils were found) (**Figure** 11.30).

Members of this community include:

- some familiar organisms such as sponges, red and green algae, and bacteria
- very few ancestors of modern animals
- many unique disk, bag, and quilt like animals which do not resemble any modern animals

The origin and relatively rapid extinction of this entire group remain somewhat of a mystery. The oxygen atmosphere and/or an ice age may explain their initial radiation. Their abrupt and nearly complete disappearance may have resulted from unbalanced predation, grazing, or competition, or yet another environmental crisis such as supercontinent breakup, changes in ocean chemistry, and/or rising sea levels. Whatever the causes, most species disappeared by the end of the Precambrian, about 542 million years ago. The Ediacarans appear to have been an early multicellular, dead-end branch on the bush of life. Their extinction, however, appears to have paved the way for a spectacular evolution of much more familiar life, which marks the beginning of the modern Phanerozoic Eon: the Cambrian explosion.

Figure 11.30: (top), an Ediacaran fossil, may be an ancestor of the trilobites. (bottom), the first accepted complex Precambrian organism, is more typical of the Ediacaran biota – it is difficult to show relationships to any modern species.

Paleozoic Era: Ancient Plants and Animals, but Seeds of Modern Life

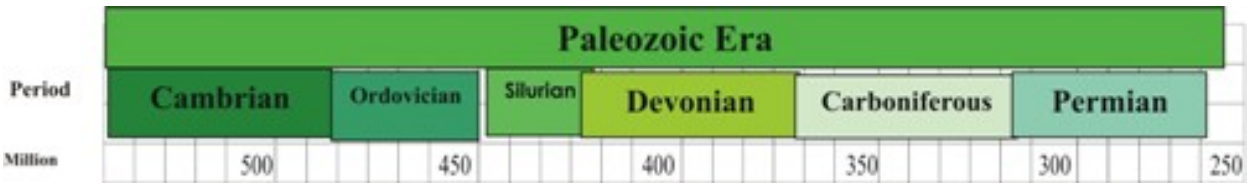

Figure 11.31

The Paleozoic era of the current, Phanerozoic Eon is the first concrete chapter of life's history (**Figure** 11.31). Abundant fossils, clearly related to modern animals, plants and fungi, illuminate the path of evolution beginning with its first Period, the Cambrian, 542 million years ago. However, the sudden appearance of such variety presents yet another puzzle in the story of life: how did roughly 50 major groups of organisms evolve so rapidly, without apparent ancestors? The abrupt emergence of so many phyla has given this period in geologic time its nickname, the **Cambrian explosion**, but its causes remain hypothetical. As for the Ediacaran radiation, major environmental changes have been proposed but not convincingly documented. A major geologic event of the Paleozoic is the amalgamation of the supercontinent Gondwana, but it does not seem to explain the extent of the increase

in Cambrian diversity. Perhaps life itself was responsible: a "critical mass" of development could have opened up new body pattern options, or more kinds of life opened more kinds of ecological niches. Whatever the cause, the evidence shows that nearly all modern animal phyla, including our own chordate phylum, are represented in this diversity of life. Among the most common and famous are reef-building sponges and arthropods, known as **trilobites** (**Figure** 11.32). Both were diverse and abundant during the Cambrian but later became extinct. However, the phyla they represent persist today.

Figure 11.32: Two representatives of more than fifty modern animal phyla from the Cambrian explosion are reef-building sponges (left) and early arthropods known as trilobites (right). Both were abundant during the Cambrian and later became extinct; however, the phyla they represent persist to this day.

A major extinction marks the boundary between the Cambrian and **Ordovician Periods** 488 million years ago (**Figure** 11.33). In warm, shallow continental seas, Ordovician life rebounded:

- A great diversity of new invertebrates swam the seas.
- **Liverworts** may have been the first green plants to appear on land (**Figure** 11.34).
- The first fish, jawless and bony-plated ostracoderms, swam slowly along shallow sea bottoms.

About 444 million years ago, a sharp drop in atmospheric CO_2 led to glaciation and ended the long stable period of warm seas. The Ice Age affected marine genera severely; up to 60% disappeared! This major extinction marks the end of the Ordovician and the beginning of the **Silurian Period**.

During the Silurian, the glaciers retreated. Melting icecaps raised sea level, yet a new supercontinent, Euramerica, formed near the equator. In a long, stable greenhouse phase, warm shallow seas covered extensive equatorial landmasses, opening tropical habitats on land and in water:

Figure 11.33: An artist's rendition shows that the second period of the Paleozoic, the Ordovician, heralded a great diversity of invertebrates, including nautiloids, crinoids, and bivalves.

Figure 11.34: Among the first true plants, liverworts colonized the land during the Ordovician. Without vascular tissue, they were small and grew flat and low to the ground (right). Like all plants and nearly all eukaryotes, they had adopted sexual reproduction (left, female reproductive organ). Both photos are greatly magnified.

- Reef-building corals and sea-scorpions evolved.
- The first jawed fishes joined armored jawless fishes and many invertebrates.
- Vascular plants solved the problem of carrying water into the air.
- Arthropods such as millipedes followed the plants onto land.

The Silurian ended about 416 million years ago with a minor extinction, which may have been due to an asteroid impact or increasing glaciation.

During the **Devonian Period**, terrestrial life expanded to include forests of clubmosses, horsetails, ferns, and the earliest seed-bearing plants and trees (**Figure** 11.35).

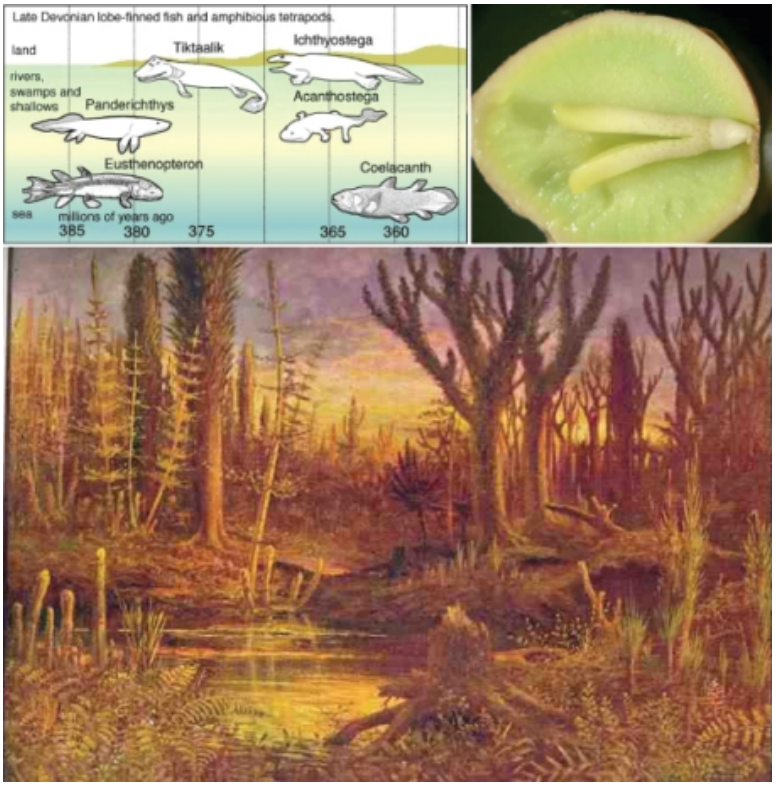

Figure 11.35: Devonian fish (above, left) evolved lobes which eventually allowed vertebrates to move to land. On land (below), clubmosses, horsetails, and ferns joined primitive seed plants and early trees to form the first forests. Seeds (above, right) allowed reproduction on dry land.

- Seeds allowed plants reproduce on dry land in the same way that shelled eggs would later help animals. Insects appeared, although they were wingless at first.
- Squid-like animals and ammonite mollusks became abundant.
- Lobe-like fins allowed some fish to lift their heads above water and breathe air in oxygen-poor waters.

About 360 million years ago, extinction struck over 20% of marine families and over 50% of all genera, ending the Devonian. One hypothesis suggests that the greening of the continents absorbed CO_2 from the atmosphere, reducing the greenhouse effect and lowering temperatures.

Extensive coal deposits, fuel for our Industrial Revolution, characterize rocks of the **Carboniferous Period** which followed. Coal developed from new bark-bearing trees in widespread lowland swamps and forests. Fallen trees were buried without decaying – perhaps because animals and bacteria had not yet evolved digestive enzymes that could break down the new molecule, lignin, in the wood. Burial of carbon lead to a corresponding buildup of oxygen in the atmosphere; O_2 at the time was an all-time high of 35% (compared to 21% today). Abundant oxygen probably encouraged evolution, especially on land.

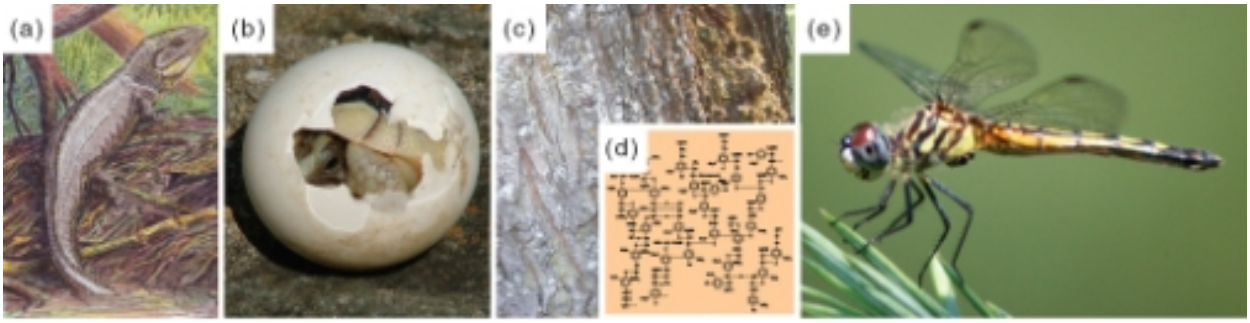

Figure 11.36: Vertebrates moved to land during the Carboniferous, and amphibians became abundant. Early lizards (A) were able to move to drier land in part because their new, shelled egg (B) did not dry out. Trees in widespread swamps evolved bark (C) containing as-yet non-biodegradable lignin (D), leading to the eventual formation of the coal which fueled our Industrial Revolution. With the highest known levels of O, giant insects such as dragonflies (E) flew the skies.

As illustrated in **Figure** 11.36:

- Giant insects took to the air.
- Vertebrates moved to land; amphibians were far larger and more abundant and diverse than today.
- The shelled egg allowed early reptiles to reproduce on land without drying out the embryo.
- Early gymnosperms, reproducing with pollen rather than sperm, colonized dry land.

Toward the end of the Carboniferous, the climate cooled. Glaciation and extinction mark the border between the Carboniferous and the last period of the Paleozoic Era, about 300 million years ago.

The **Permian** is best known for the dramatic event which ended not only the period but also the entire Paleozoic Era – an extinction of 95% of the then-living world. If we look more

closely at the effects of continental geography on climate, perhaps we can begin to understand not only that massive extinction, but also the major events in evolution which preceded it. During the Permian, all the major landmasses of earth combined into a single supercontinent, known as **Pangaea** (**Figure** 11.37). As for today's continents, much of the interior would have been dry with seasons of temperature change, because the oceans' moderating effects were too distant. Pangaea's size may have exaggerated this continental climate of seasons and drought. Three major groups of animals and plants evolved in response to Pangaea's extensive arid niches.

Figure 11.37: The supercontinent Pangaea encompassed all of today's continents in a single land mass. This configuration limited shallow coastal areas which harbor marine species, and may have contributed to the dramatic event which ended the Permian - the most massive extinction ever recorded.

- Reptiles, with claws, scaly skin, and shelled eggs, diversified, foreshadowing Mesozoic dinosaurs.
- Cycads and other gymnosperms, with cuticle-covered leaves to limit water loss and cones to bear seeds, dominated forests.
- Insects evolved entire life cycles on dry land; beetles and flies navigated land and air.

At the end of the Permian, an estimated 99.5% of individual organisms perished. Several factors may have contributed, and one factor relates again to Pangaea. Marine biodiversity is greatest in shallow coastal areas. A single continent has a much smaller shoreline than multiple continents of the same size. Perhaps this restriction of marine habitats contributed to the drastic loss of species, for up to 95% of marine species perished, compared to "only" 70% of land species. Another factor might have been massive basalt flow attributed to the time, which could have increased CO_2 levels to precipitate global warming. Some scientists invoke

extraterrestrial causes: a huge meteorite crater discovered in 2006 in Antarctica and dated to between 100 and 500 million years ago could represent an impact which darkened skies, decreased sunlight, and shut down photosynthesis. Although the cause remains unknown, fossils clearly document the fact of Earth's most devastating extinction. The event closed the Paleozoic Era, and inevitably opened the door to a new burst of life in the Mesozoic.

Mesozoic Era: Age of the Dinosaurs

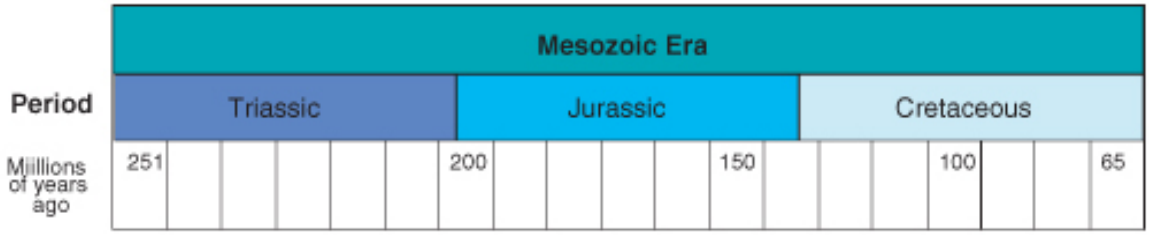

Figure 11.38

Following the "great dying" at the end of the Permian, a resurgence of evolution in the Mesozoic established the basis of modern life (**Figure** 11.38). The continents, which began as one, broke apart and eventually shifted into their present configuration. Rifting encouraged speciation (**Figure** 11.39). Relatively stable warm temperatures contributed once again to great diversification among animals.

Figure 11.39: A major geological change in the Mesozoic was the breakup of the supercontinent Pangaea into Laurasia and Gondwana, and eventually into the continents we know today. The breakup created new niches, contributing to speciation.

During the **Triassic**, early dinosaurs appeared on land as the archosaurs, in the ocean as ichthyosaurs, and in the air as pterosaurs (**Figure** 11.40). One line of reptiles gave rise to

the first mammals and others to the earliest turtles and crocodiles. Seed ferns and conifers dominated the forests. Modern corals and fishes, and many modern insects, evolved. The Triassic gave way to the Jurassic with one of the most active periods of volcanism ever recorded. Pangaea began to break apart. The major extinction marking the border between these two Periods opened niches which made way for the Age of the Dinosaurs.

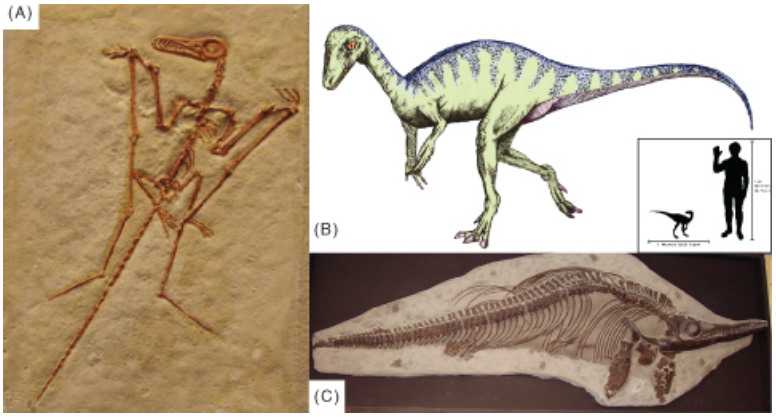

Figure 11.40: Early dinosaurs branched off from other reptiles in the Triassic. The dinosaurs radiated into diverse niches – many undoubtedly newly opened by the massive Permian extinction. Pterosaurs (A) inhabited the air, archosaurs (B) the land, and ichthyosaurs (C) the seas. Not all dinosaurs were giant, as the size comparison of archosaurs to the average adult human (B, inset) shows.

The **Jurassic Period** was the golden age of the large dinosaurs which lived amidst warm, fern-and cycad-filled forests of pines, cedars, and yews (**Figure** 11.41). Dinosaurs included widespread and huge herbivorous sauropods, smaller predatory theropods, stegosaurs, and pterosaurs. Ichthyosaurs and plesiosaurs thrived in the oceans. Ammonites, sea urchins, and starfish were abundant invertebrates. The first birds and lizards appeared. One of the most famous transition fossils, **Archaeopteryx**, with characteristics of both reptiles and birds, dates from this Period (**Figure** 11.42). During the Jurassic, the supercontinent Pangaea broke apart into Laurasia and Gondwana.

Flowering plants first appeared in the Jurassic, but dominated the last, **Cretaceous Period** of the Mesozoic.

- New kinds of insects coevolved with the flowering plants, serving as their pollinators.

An early example of this coevolution is the magnolia, which developed flowers to attract – and withstand feeding damage from - beetle pollinators. Bees first appeared during the Cretaceous, and figs evolved unusual flower-fruits in concert with tiny wasp pollinators (**Figure** 11.43).

Figure 11.41: The Jurassic was the golden age of large dinosaurs. Coniferous trees, also huge, and fern and cycad swamps formed their habitats.

Figure 11.42: One of the most famous of all transitional fossils is "ancient wings." The fossil dates back to the Jurassic. Both reptilian features (teeth and claws) and avian features (wings and feathers) are clear.

Figure 11.43: Plants first evolved flowers during the Cretaceous. Flowers attracted and fed insects, and insects, in turn, pollinated the flowers, leading to a long coevolutionary relationship. Cretaceous examples include the magnolia and its beetle pollinators (left and below), and the unique fig "fruit"-flower and its tiny wasp pollinator (top right).

- Primitive birds arose from reptilian ancestors and soon out-competed many of the pterosaurs.
- All three major groups of mammals – **monotremes**, **marsupials**, and **placentals** – became established, but remained small.

In part because a huge sea (the Tethys) formed an east-west connection between the oceans, Cretaceous climate was uniformly warm; even the poles lacked ice. In response, warm-adapted plants and dinosaurs expanded to within 15 degrees of the poles. Dinosaurs reached a peak of diversity and size (**Figure** 11.44 and **Figure** 11.45).

- Titanosaurs, including possibly the largest of all the dinosaurs, the 100-ton *Argentinosaurus*, were the dominant herbivores. A single *Argentinosaurus* vertebra was 1.3 meters long, and its tibia would have been as tall as some humans. Fossilized eggs, containing embryos with skin, indicate that titanosaurs were colonial nesters. Fossilized dung shows they ate cycads and conifers, but also palms and the ancestors of rice and bamboo; some scientists suggest that dinosaurs and grasses coevolved like insects and flowering plants.
- One of the largest predatory dinosaurs,*Giganotosaurus*, weighed "only" 5.2 tons, but in length surpassed *Tyrannosaurus* rex by two meters (six feet). *Giganotosaurus'* skull was the size of a bathtub, but its brain was the size and shape of a banana! What were they *thinking*?

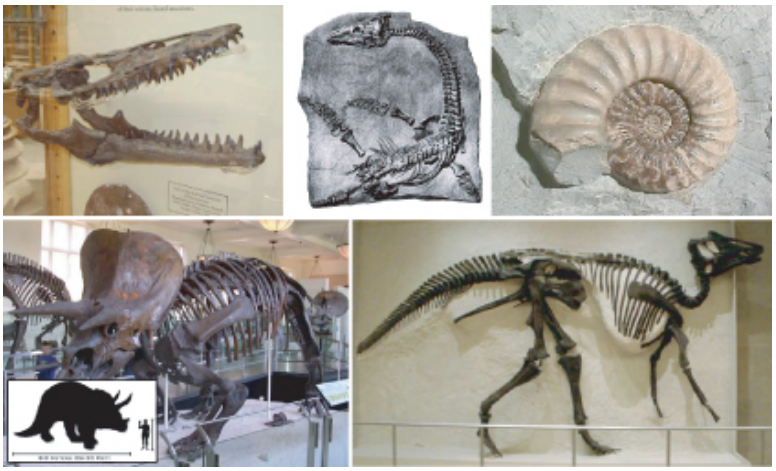

Figure 11.44: Many kinds of reptiles and invertebrates lived during the Cretaceous Period. Mosasaurs (upper left), plesiosaurs (center) and ammonites (upper right) swam the seas with modern sharks. Triceratops (lower left) and duckbilled dinosaurs (lower right) show some of Cretaceous diversity in dinosaurs.

Figure 11.45: Moderate climate worldwide during the Cretaceous encouraged great size and diversification among dinosaurs. The herbivorous titanosaur, (above) may have been the largest of all the dinosaurs, weighing in at up to 100 tons. (below) probably preyed upon titanosaurs such as , but weighed "only" 5.2 tons, and despite a bath-tub-sized skull, operated on a brain the size of a banana.

The dramatic extinction of all dinosaurs (except the lineage which led to birds) marked the end of the Cretaceous. Dinosaurs had begun to decline earlier, perhaps due to reduction in atmospheric oxygen and global cooling. A worldwide iridium-rich layer, dated at 65.5 million years ago, provides evidence for an additional, more dramatic cause for their ultimate extinction. Iridium is rare in the Earth's crust, but common in comets and asteroids. Scientists correlate this layer with a huge crater in the Yucatan and Gulf of Mexico. A collision/explosion between the Earth and a comet or asteroid could have spread debris which set off tsunamis, altered the climate (including acid rain), and reduced sunlight 10-20%. A consequent reduction in photosynthesis would have caused a drastic disruption in food chains. Some scientists believe that volcanism also contributed to the **"K-T"** (Cretaceous-Tertiary) **extinction**, but most agree that "an impact event" was at least a major cause (**Figure** 11.46). The massive extinction and sharp geologic line led geologists to define the end of the Mesozoic and the beginning of our modern Era, the Cenozoic, with this event.

Figure 11.46: The extinction of the dinosaurs at the end of the Cretaceous is attributed at least in part to an impact event which could have involved a meteor, an asteroid, or a comet.

Cenozoic Era: Age of Modern Life

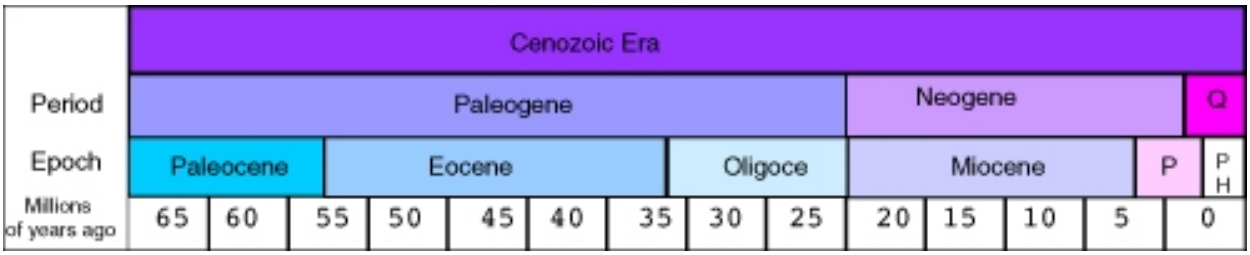

Figure 11.47

Neogene and Quaternary (Q) Periods share part of the Pliocene Epoch (Pl). Pleistocene

(P) and Holocene (H) Epochs complete the Quaternary Period. Divisions in this part of the Time Scale are debated and may change.

The **Cenozoic Era** brings the history of life into the present, but not without drama, mystery, and the looming possibility of a "Sixth Extinction" (**Figure** 11.47) You probably know the basic story: mammals took over where dinosaurs left off, branched to form primates, moved to the grasslands, became human-like, survived the ice ages, and the rest is – literally – history. Let's look at some of the major events, focusing not only on our immediate ancestors but also on the world in which they evolved. More detailed stories of the evolution of humans and other groups will be told in later chapters.

Seven Epochs comprise the Cenozoic Era, with the Holocene continuing up to today. "Tertiary" refers to the 64 million years and five epochs before the Quaternary Period, well known for its recent ice ages and recognizable humans. Tertiary and Quaternary periods could be called suberas, but current organization of the Cenozoic segment of the Geologic Time Scale is the subject of current debate; it may well change.

The **Paleocene Epoch** provided a worldwide warm, humid climate for the rapid evolution which followed the extinction of the dinosaurs (**Figure** 11.48). Many plants, herbivores, and carnivores had disappeared because they depended on photosynthesis, but omnivores, insectivores, and scavengers – which included many mammals and birds – survived because their food sources actually increased. Mammals radiated into the ecological niches opened up by the extinction of herbivores and carnivores, and larger species, up to bear- or hippopotamus-sized, began to appear In equatorial regions, the first recognizably modern rain forests appeared, and south of the equator, hot arid regions provided niches for new groups of plants, including cacti.

Volcanism or a massive release of methane gas trapped in the oceans may have triggered one of the most rapid global warming events ever measured at the beginning of the **Eocene**, 56 million years ago. CO_2 from either volcanism or oxidation of methane would have caused the oceans to become more acidic, and Earth's temperatures to rise. Warm temperatures allowed forests of dawn redwood, swamp cypress, and palms to extend toward both poles. In the interiors of the continents, seasonal temperature and moisture variations led to the evolution of grasses, expansive savannas and deciduous forests. Within these new ecosystems, modern mammals with specialized teeth evolved. Probably due to high temperatures, these mammals were smaller than those who preceded them – or those who followed:

- Horses and tapirs evolved in North America, and rhinoceros evolved in Asia.
- Primates, with their long arms and legs and grasping hands and feet, appeared.
- Mammals returned to the sea; *Basilosaurus* was an ancestor of today's whales.

At the beginning of the Eocene, Australia was still connected to Antarctica, but when they broke apart, ocean currents changed and cooling began in earnest, foreshadowing the ice ages to come. Tundra ecosystems developed near the poles. Falling sea levels, a land bridge

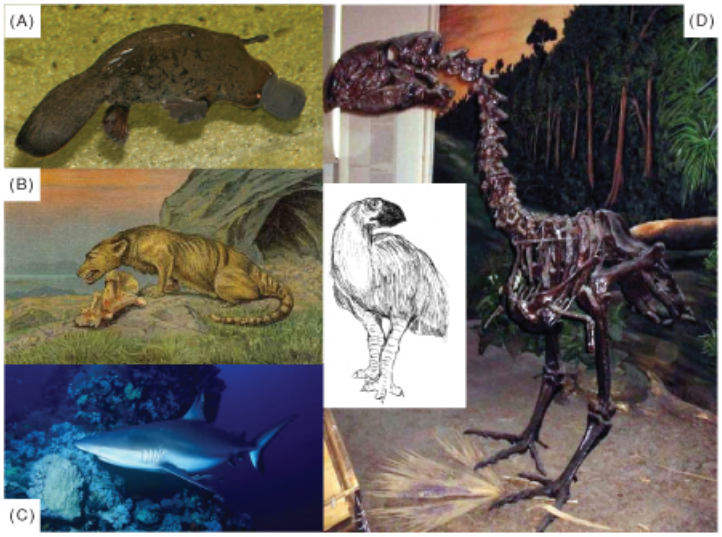

Figure 11.48: During the Paleocene, mammals and birds invaded ecological niches formerly occupied by the dinosaurs. Mammals included monotremes (A), marsupials, and hoofed placentals (B). Modern sharks (C) patrolled the seas. Birds included the giant flightless (D).

immigration of mammals from Asia to North America, and perhaps several impact events led to an extinction which marks the end of this epoch.

As its name implies, the Oligocene Epoch produced a "few" new mammals, especially in grasslands and savannahs (**Figure** 11.49).

- Pig-like entelodonts used massive skulls to crush bones of scavenged prey.
- One of the largest land mammals of all time, the 18-foot, 15 ton *Indricotherium*, ate leaves from the tops of trees in the manner of a giraffe.
- Horses, represented by *Mesohippus* remained small relative to today's species.
- Large terrestrial carnivores such as *Hyaenodon*, hunted mammals up to the size of sheep.
- The rhinoceros-like *Arsinoitherium* wandered tropical rain forests and swamps.

By the beginning of the **Miocene Epoch** 23 million years ago, the continents had almost assumed their current configuration, except that North and South America did not connect. Oceans continued to cool, ice caps expanded at the poles, and consequently the climate dried. Grasslands, needing less rain, replaced forests, and large herbivores coevolved with the grasses. Modern mammals, including wolves, beaver, deer, camels, seals, dolphins, and porpoises, evolved. Up to 100 species of apes lived throughout Africa, Europe, and Asia. Almost all modern bird groups were represented.

The Earth's climate continued to cool into the **Pliocene**, the epoch in which hominids first

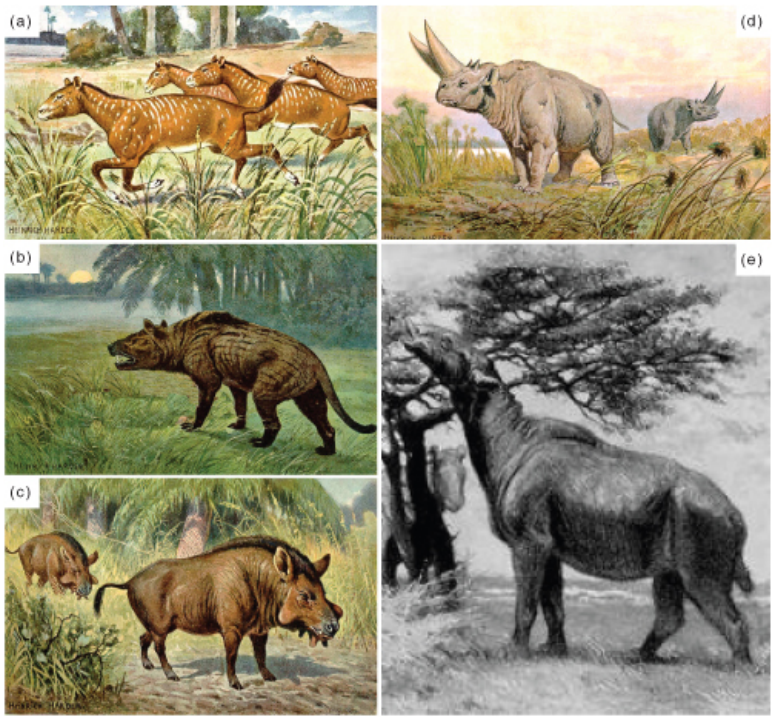

Figure 11.49: The Oligocene produced fewer new mammals than the Eocene; most were adapted to grasslands. (A) showed small steps toward modern horses. (B) had the large, sharp teeth of a carnivore. (C) was a piglike scavenger, and (D) was a large relative of elephants and hyraxes. Perhaps the largest land mammal of all time resembled an overweight giraffe; (E) weighed up to 15 tons and reached 18 feet in height.

appeared. Seasons became more pronounced; deciduous forests and grasslands replaced tropical forests, and coniferous forests and tundra expanded. Large mammals, such as browsing mastodons and grazing mammoths, roamed the grasslands and tundra. Into this setting walked Australopithecines, such as **Lucy** who share common ancestry with humans. Fossil footprints dated as 3.7 million years old establish Australopithecenes as bipedal – perhaps the first apes to walk upright (**Figure** 11.50). Later Pliocene hominids included two members of our own genus, *Homo rudolfensis* and *Homo habilis*. During this epoch, falling sea levels exposed two land bridges which allowed important migrations.

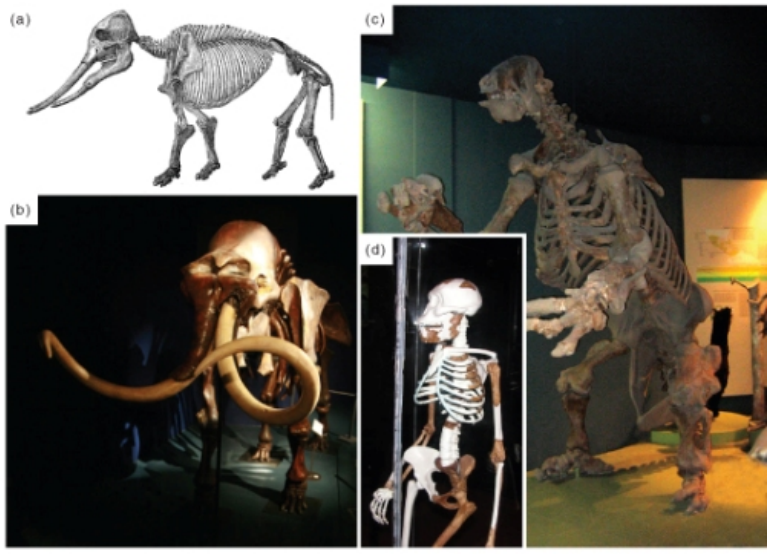

Figure 11.50: Lucy (D) is one of the most complete fossils of , a human relative also known for fossil footprints which establish an upright posture. Note that the brown bones are Lucy's; others have been added to restore her skeleton. Australopithecines coexisted (but not necessarily on the same continent!) with browsing mastodons (A), grazing mammoths (B), and giant herbivorous sloths (C).

- One allowed horses, mammoths, mastodons and more to migrate between Asia and North America.
- A second allowed North American placental mammals, such as giant sloths, armadillos, and sabertooth cats, to migrate to South America. Placentals eventually out-competed all of South America's marsupials except the opossum.

Repeated glaciations define the **Pleistocene Epoch**. Glaciation tied up huge volumes of water in ice packs; rainfall was less, because evaporation was less. Deserts were relatively dry. During interglacial periods, huge inland lakes and rivers held or carried the melt waters, and coastal flooding reduced land area. During the four major glaciations, these severe climate changes stressed animals and plants, encouraged the evolution of large animals (the **Pleistocene megafauna**), and forced life toward the equator.

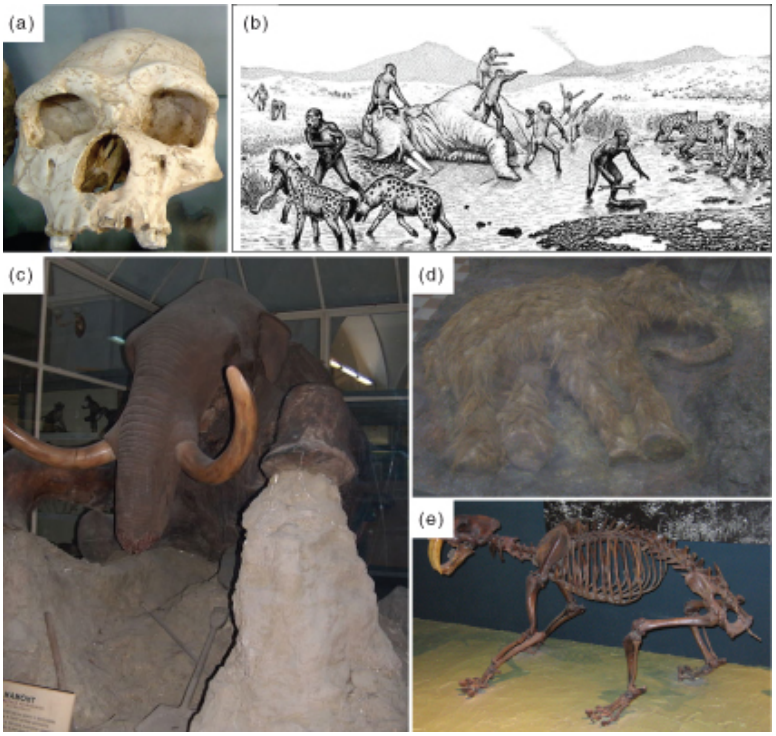

Figure 11.51: That (A), and later (or in other parts of the world) , hunted mammoth (B) is shown by fossil evidence 1.8 million years old. Woolly mammoths (C), specially adapted to cold climate, were probably hunted, as well, as humans spread throughout the world. Nearly 40 woolly mammoth remains have been found preserved in permafrost, complete with soft tissue and DNA. To date, mitochondrial DNA has been sequenced. The calf (D) measures 2.3 meters (8 feet) long. A predatory competitor to humans was the saber-tooth tiger, (E).

- Some adapted to the cold: the Woolly Mammoth grew thick, shaggy hair oiled by abundant sebaceous glands, a layer of fat beneath the skin, smaller ears, and even a convenient flap to cover the anus, keeping out the cold. Mammoth teeth ground tough tundra grasses, and their long, curved tusks may have helped to clear snow. Permafrosts have preserved nearly 40 mammoth remains, including soft tissues, and scientists actually hope to be able to recreate its genome; mitochondrial DNA for one species has already been sequenced! Using this sequence as a molecular clock, scientists calculate that mammoths diverged from African elephants about 6 million years ago, roughly the same time that humans diverged from chimpanzees.
- Saber-tooth cats used dagger-like teeth to cut their prey's windpipe and jugular veins, causing death by bleeding. Many saber-tooths have been found in the LaBrea Tar Pits in southern California, where they had tried to feed on mammoths trapped before them in the sticky tar/asphalt.
- *Homo erectus,* the dominant hominid during the Pleistocene, migrated throughout Africa, Europe, and Asia, giving rise to a number of variations of hominids. Although *Homo erectus* was probably the first hominid to leave Africa, the species may not have been a direct ancestor of humans. Pleistocene hominids were hunter-gatherers; evidence dated at 1.8 million years ago supports their consumption of mammoth.

A major extinction of Pleistocene megafauna continued into the Holocene. Some attribute the extinction to changing climate or disease, but others have connected the migrations of humans to each continent's time of extinction The "overkill" theory suggests that humans hunted large animals with too much success. Agreement is not yet universal, but most scientists admit the evidence is strong.

The current **Holocene Epoch** began 11,550 years ago (about 9600 B.C.) with the retreat of the Pleistocene glaciers. During the Holocene, melting ice has raised sea level over 180 meters (600 feet). Geologists believe that we are currently experiencing an interglacial warming, and that glaciers will return – unless continued human burning of fossil fuels raises CO_2 levels to bring about global warming. All of human civilization has occurred within the Holocene; *Homo sapiens* have passed through Mesolithic, Neolithic, and Bronze Age civilizations. Human evolution will be discussed in more detail in a future chapter, but here we will examine the possibility that humans are currently causing a mass extinction which some compare to the Permian. Many would include the Pleistocene megafauna in this "Sixth Extinction," citing the "overkill theory" data in **Figure** 11.52. Some even call the period of time from that loss to the present the "Anthropocene epoch" to describe the major impact humans have had on the planet and its life. Human population has surpassed 6.6 billion, and over-fishing, climate change, industrialization, intensive agriculture, and clearance of grasslands and rainforests contribute to a startlingly high loss of life.

Paleontologists estimate that background extinction rates throughout most of life's history averaged between 1 and 10 species per year (**Figure** 11.53) . The present rate of extinction is thought to be 100 to 1000 times "background" rates, suggesting that the number of species which currently disappear *each year* could exceed 1,000! Biologist E.O. Wilson has predicted

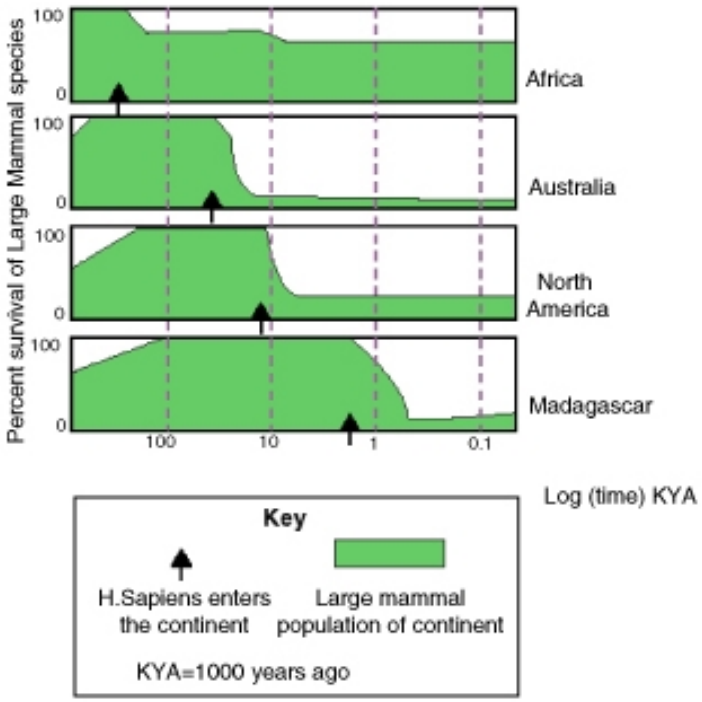

Figure 11.52: This data comparing the arrival of humans to the decline of the Pleistocene megafauna supports the "overkill" theory that human predation contributed to the extinction of large mammals throughout the world. Other theories involve climate change and disease.

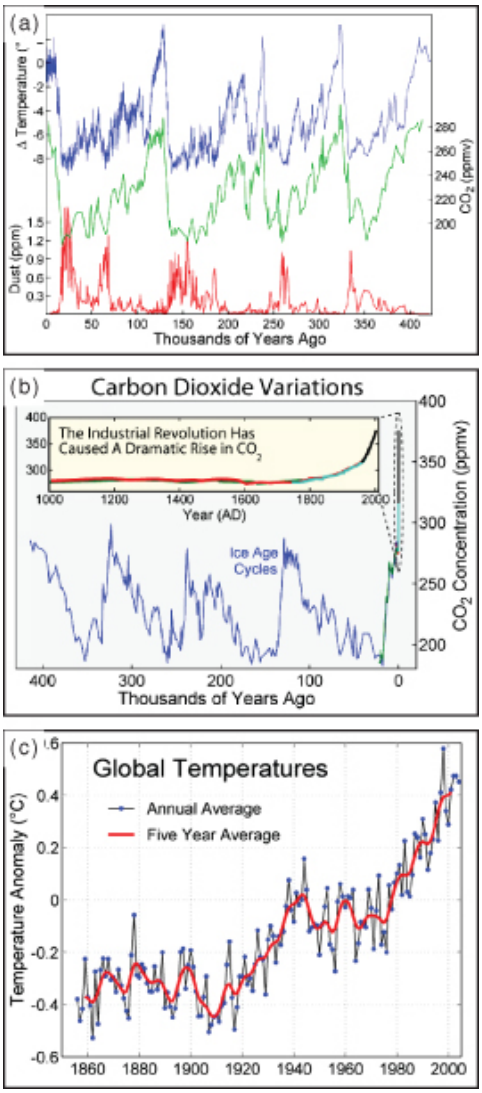

Figure 11.53: (A) Changes in CO levels (green) are clearly associated with temperature changes (blue); the graph shows the four major Ice ages of the Pleistocene. Graphs B (long time scale) and C (recent time) show increases in CO and global temperature over the past 150 years, suggesting that the Industrial Revolution, which began our major fossil fuel burning and release of CO, may account for much of the increase in temperature – a new, human–induced global warming.

that current rates will result in the loss of over half of life's biodiversity within the next one hundred years. In contrast, Earth's shortest previous extinctions spanned several hundred thousand to several million years, and evidence for cause is entirely geological in nature. No other species has influenced the Earth and its life as powerfully as *Homo sapiens.*

Others say there is ample evidence – evidence discussed in this lesson – to show that extinction is a natural phenomenon which has occurred repeatedly throughout the history of life on Earth. They point to the recoveries – indeed, radiations – which filled vacated ecological niches after each event.

However, those who are concerned about the current extinction wonder whether or not humans will be one of the species to become extinct. Because we are the only surviving members of our family, recovery or radiation would not be an option.

What do you think?

Lesson Summary

- After 3 billion years, life was unicellular but included all 3 major lineages: Bacteria, Archaea and Eukaryotes; all of multicellular evolution occurred within the last billion years.
- Plant, animal, and fungal ancestors diverged as solitary cells.
- Colonies of eukaryotic cells and specialized cells evolved; *Volvox* illustrates this level of evolution.
- Sexual reproduction appeared a little over 1 billion years ago, providing more variation for natural selection.
- By about 1 billion years ago, true (multicellular) plants emerged, and 100 million years later, true animals.
- 600 million year old Ediacaran fossils illustrate diverse early animal life, but few are related to modern animals.
- The Cambrian explosion was the sudden appearance of great diversity in animals, plants, and fungi clearly related to modern species, due to lower O_2, global warming, plate tectonics, and a critical mass of biotic change.
- During the Ordovician, liverworts became the first land plants, and jawless, bony-plated fish joined a variety of invertebrates in warm seas.
- Ferns and the first seed plants forested the land in the Devonian; in shallow seas, jawed fish evolved lobed fins.
- Extensive coal deposits and an all-time high level of atmospheric O_2 characterized the Carboniferous Period. Giant insects, early gymnosperms with pollen, and vertebrates with shelled eggs colonized dry land.
- During the Permian, all the major landmasses of earth combined into a single supercontinent, Pangaea. A continental climate of seasons and drought favored reptiles, gymnosperms, and insects such as beetles. The Permian ended with the most massive

extinction of all time; 99.5% of all species disappeared, opening the door for a new radiation of species in the Mesozoic.

- The Permian extinction, stable temperatures and continental breakup created niches for a great radiation of life in the Triassic Period. Reptiles diversified – on land as the archosaurs, in the air as pterosaurs, and in the seas as ichthyosaurs. Other reptilian lines gave rise to early turtles, crocodiles, and finally, mammals and birds.
- During the Cretaceous, primitive birds began to radiate and out-compete the pterosaurs; dinosaurs reached their largest size and greatest diversity.
- Record-high temperatures during the Eocene made way for hoofed animals and primates within grasslands, savannas, and deciduous and coniferous forests.
- *Australopithecus*, perhaps the earliest, upright hominid, appeared during the Pliocene. Global cooling and glaciation led to a drop in sea level, exposing two land bridges which allowed important animal migrations.
- Cycles of glaciation stressed Pleistocene animals and plants; some, like the woolly mammoth, adapted to cold and others, like *Homo erectus*, the dominant hominid, migrated throughout Africa, Europe, and Asia.
- As the human population climbs above 6.6 billion, we may be causing a Sixth Extinction of life on Earth.

Review Questions

1. What major evolutionary steps followed the evolution of the first eukaryotic cell during the late Precambrian to set the stage for the "Cambrian explosion?"
2. List the global environmental factors which influenced the evolution of multicellular life.
3. Discuss and give examples of the relationships among the environmental factors you listed above. Include their major effects on the history of life.
4. Describe the conditions under which the dinosaurs emerged to dominate life on Earth, and identify the diversity of habitats and niches occupied by the dinosaurs during their "golden age."
5. What famous example of coevolution began in earnest during the Cretaceous? Give two early examples.
6. Cite and evaluate the evidence for an "impact event" as the primary cause of the K-T extinction.
7. Analyze the emergence of mammals and birds as dominant land animals during the early Cenozoic.
8. How does the Cenozoic climate explain the emergence of grassland and tundra and their megafauna?
9. Give two examples of how land bridge formation can affect evolution.
10. Discuss the factors which are contributing to the current major extinction, and analyze your own response to E.O. Wilson's description of the "Sixth Extinction."

Further Reading / Supplemental Links

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Vocabulary

Archaeopteryx One of the most famous transition fossils; has characteristics of both reptiles and birds.

Cambrian explosion The abrupt emergence of many new species during the Cambrian Period.

liverworts Among the first true plants; colonized land during the Ordovician.

Jurassic Period The golden age of the large dinosaurs which lived amidst warm, fern-and cycad-filled forests of pines, cedars, and yews.

Lucy One of the most complete fossils of *Australopithecus afarensis*, a human relative also known for fossil footprints which establish an upright posture.

marsupials One of the three major groups of mammals.

monotremes One of the three major groups of mammals.

Pangaea A single supercontinent formed from all the major land masses of Earth; formed during the Permian.

placentals One of the three major groups of mammals.

trilobites Common arthropods which were diverse and abundant during the Cambrian Period.

Points to Consider

- The study of the history of life attempts to answer the age-old question: where did we humans come from? What are some of the answers our current knowledge gives us? What points are still missing?
- To what extent has life itself influenced the history of life on Earth? Consider some specific effects certain kinds of life have had on climate, the atmosphere, and certain species.
- At least some mammoth DNA has been preserved in permafrost. What do you think about the idea of re-creating animals such as the mammoth from the past – as fictionalized in Jurassic Park?
- Do you think extinction plays an essential role in evolution? Is it a negative or positive role?
- Do you judge the Sixth Extinction to be an important problem? Do you think it is significantly different from earlier extinctions?

Image Sources

(1) USGS. http://commons.wikimedia.org/wiki/Image:Laurasia-Gondwana.png. Public Domain.

(2) *http://commons.wikimedia.org/wiki/Image:Asaphiscuswheelerii.jpg*. GNU-FDL,GNU-FDL.

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Chapter 12

Evolutionary Theory

12.1 Lesson 12.1: Darwin and The Theory of Evolution

Lesson Objectives

- Identify important ideas Darwin developed during the voyage of the *Beagle*, and give examples of his observations that supported those ideas.
- Recognize that scientific theories and discoveries are seldom the work of just one individual.
- Describe prevailing beliefs before Darwin about the origin of species and the age of the earth.
- Evaluate Lamarck's hypothesis about how species changed.
- Analyze the impact of Lyell's *Principles of Geology* on Darwin's work.
- Evaluate the influence of Malthus' ideas about human population on Darwin's thinking.
- Discuss the relationship between Alfred Russel Wallace and Charles Darwin.
- Describe the general ideas of Darwin's Theory of Evolution.
- Use Darwin's reasoning to explain natural selection as the mechanism of evolution.
- Explain how natural selection results in adaptation to environment.
- Recognize the importance of variation to species survival.
- Relate the idea of differential survival to the concept of natural selection.
- Interpret the expression "descent with modification."
- Discuss the concept of "common ancestry."
- Show how Darwin's theory provides a scientific explanation for the fossil record.
- Interpret Darwin's theory as an example of the general principle that the present arises from the materials and forms of the past.

Introduction

Charles Darwin's **Theory of Evolution** represents a giant leap in human understanding. It explains and unifies all of biology – thousands of years of natural history from before Darwin's time, as well as the 150 years of genetics, molecular biology, and even ecology since Darwin published the theory. It directs our responses to disease and our practice of agriculture. It enlightens conservation biology. It has the potential to guide our future decisions about biotechnology. Apart from science, the Theory of Evolution has dramatically changed how we think about ourselves and how we relate to the world. Because the theory has influenced so many aspects of human life, it is crucial that you understand it thoroughly.

The "Theory of Evolution" contains two major ideas:

The first is evolution itself.

1. Present life has arisen gradually from past life forms. The millions of species of plants, animals, and microorganisms that live on Earth today are related by descent from common ancestors.

The second describes how evolution happens.

1. **Natural selection** explains how the diversity of life has arisen through time.

The main goal of this lesson will be to clarify these ideas. The lesson will begin by exploring Darwin's experiences. The ideas of others who influenced Darwin's thinking will also be presented. Finally, the content and significance of the theory itself will be analyzed.

The Voyage of the Beagle

Captained by a 26-year-old Royal Navyman and carrying a 22-year-old "gentleman's companion" who collected beetles competitively, His Majesty's Ship *Beagle* set sail on one of the shortest days of the year 1831 to chart South American coastal waters. Alarmed by the suicides of his own uncle and the previous *Beagle* commander, Captain Robert FitzRoy had sought a social and educational equal to accompany him at dinner and in scientific endeavors throughout the anticipated two-year voyage. Charles Darwin, financed by his wealthy father, assumed the unpaid positions of the ship's naturalist and captain's friend.

Darwin resisted his family's hopes that he become a doctor or clergyman. During the two years before he dropped out of medical studies, he was repulsed by the brutality of surgery but fascinated by natural history – field observations of plants, animals, rocks, and fossils. He observed marine mammals on the English coast, and learned taxidermy from a freed slave whose talk of rain forests ignited curiosity in Darwin. After his disappointed father switched him to a school of theology, Darwin again gravitated toward natural history,

Figure 12.1: The HMS carried 22-year-old Charles Darwin as an unpaid naturalist and "gentleman companion" for the ship's captain.

becoming a protégée of botanist John Steven Henslow in order to learn the popular pastime of competitive beetle collecting. He managed to pass his theology exams, but his interests continued to reflect his passion for natural history, including William Paley's "argument for divine design in nature." He had just postponed entry into the clergy in order to study geology – mapping rock layers in Wales – when he received the invitation to join FitzRoy on the *Beagle*.

Planned to last two years, the voyage shown in **Figures** 12.1 and 12.2, stretched to five years. Darwin spent over 3 years of this time on land, carefully observing rock formations and collecting animals, plants, and fossils (**Figure** 12.4). Throughout the journey, he used his observations to develop a series of ideas which later became the foundation for his theory of evolution by natural selection (**Figure** 12.5). A few of his ideas, observations, and experiences follow.

Rock and Fossil Formations

During the voyage of the *Beagle*, Darwin made a number of geological observations that helped form his theory. Rock and fossil formations that he observed suggested that continents and oceans had changed dramatically over time.

- Darwin found rocks at a continental divide, 13,000 feet *above* sea level, which contained fossil seashells.
- A river in Argentina rose gradually through a series of plateaus, which Darwin and FitzRoy interpreted as ancient beaches.
- After experiencing a volcanic eruption and an earthquake in Chile, Darwin found a

Figure 12.2: The s voyage continued for nearly five years, although original plans called for only two. Darwin spent over three years of that time on land, collecting plants, animals, and fossils, and developing his ideas about evolution and natural selection.

bed of newly dead mussels, which the quake had lifted nine feet above the sea.

- A petrified forest embedded in sandstone at 7,000 feet had been a sunken coastal woodland, buried in sand and then uplifted into mountains.
- Near Lima, Darwin recognized coral atolls as the result of sinking volcanoes, with coral adding layer after layer to keep the living reef close to the sunlit surface, as shown in **Figure** 12.3.

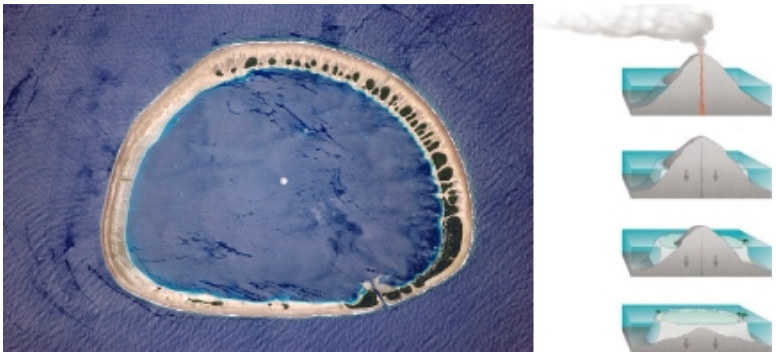

Figure 12.3: Darwin explained coral atolls in terms of slowly sinking volcanoes. Evidence for slow geologic change contributed a great deal to his thinking about slow changes in life.

Tropical Rain Forests and Many New Plant, Animal, and Fossil Species

During the voyage of the *Beagle,* Darwin made a number of observations of plants, animals, and fossils that helped him form his theory. Observations of tropical rain forests and many new plant, animal, and fossil species encouraged Darwin to reconsider the source of the vast diversity of life.

- In Brazil, Darwin collected great numbers of insects – especially beetles!
- Inland from Montevideo, Darwin dug up the hippopotamus-like skull of an extinct giant capybara.
- After collecting his first marsupial in Australia, Darwin exclaimed that some people might think "'Surely two distinct Creators must have been [at] work."

Figure 12.4: Marine Iguanas (left) and Blue-footed Boobies (right) were among the tremendous variety of new and very different plants and animals Darwin identified during the voyage of the . He developed his ideas about evolution and natural selection to explain the remarkable similarities and differences he had observed.

Native Cultures Raised Questions

During the voyage of the *Beagle*, observations of native cultures led Darwin to question the relationship between humans and animals and the development of civilizations.

- Disgusted by the enslavement of blacks in Brazil, Darwin argued with FitzRoy so fiercely that the captain temporarily banished him from dining.
- At the tip of South America, Darwin wrote "I could not have believed how wide was the difference between savage and civilized man: it is greater than between a wild and domesticated animal."
- Darwin described New Zealand Maoris as savage, in contrast to missionary-influenced Tahitians.

- Jemmy Buttons, a South American native who had "been civilized" in England, chose to stay in South America rather than continue with the *Beagle* - to the great dismay of the Englishmen convinced of their civilization's superiority.

Figure 12.5: Darwin's encounters with native cultures influenced his thinking as much as his discoveries of fossils and new species. This painting was taken from original pictorial records of the voyage.

Sedimentary Rocks Implied Gradual Changes

Darwin also made a number of observations that implied gradual changes in both the Earth and in living organisms, as opposed to catastrophic changes, including:

- Many inland sediments had clearly been deposited by quiet tides rather than catastrophic floods.
- Gauchos, cowboys of Argentina, helped Darwin find and excavate fossils of gigantic extinct mammals, including armadillos and one of the largest mammals of all time, the ground sloth *Megatherium* (**Figure** 12.6). Darwin recorded that these sediments bore no trace of a Biblical flood.

Figure 12.6: Darwin found two separate fossils of one of the largest mammals of all time, a giant ground sloth, . He noted that they were found in sediments which had been deposited slowly over long periods of time, rather than suddenly as by a catastrophic flood.

Life on Island Chains

The distribution of life on island chains challenged the dogma of the unchangability of species. The Galapagos Islands are arguably where Darwin made his most influential observations. The Galapagos Islands are a group of 16 volcanic islands near the equator about 600 miles from the west coast of South America. Darwin was able to spend months on foot exploring the islands.

- Darwin noted that locals could distinguish each island's variation of Galapagos tortoise, shown in **Figure** 12.7. Surprisingly, he did not collect their shells, despite dining on the giant reptiles during the voyage.
- A series of birds now known as the Galapagos (or Darwin's) finches were also specific to certain islands. Darwin failed to label the locations in which he had collected these rather drab-looking birds, but fortunately, FitzRoy and the ship's surgeon were more careful with their collections.
- Darwin interpreted the different Galapagos mockingbirds as varieties, but wrote that if varieties were a step on the way to new species, "such facts (would) undermine the stability of Species."

Figure 12.7: Like many seamen, Darwin and the crew of the dined on Galapagos tortoise, a convenient animal to carry live on long voyages. However, locals living on the islands claimed the tortoises varied according to the islands from which they came, and this idea later played an important role in Darwin's thinking about the origins of species.

Throughout the trip, Darwin shown in **Figure** 12.8, sent his mentor, Henslow, collections of plants, animals, insects, and fossils – many of which were previously unknown. While Darwin traveled, Henslow promoted his work by sharing his geological writings and fossils with renowned naturalists. By the time the *Beagle* returned to England in October of 1836, Darwin himself had been accepted as an established naturalist. His father set up investment accounts to fund his son's career as a "gentleman scientist." At that time, governments and universities did not fund scientific research, so only independently wealthy individuals could afford to practice pure science. This position gave Darwin the contacts, resources, and freedom he needed to develop his ideas into the theory of evolution by natural selection.

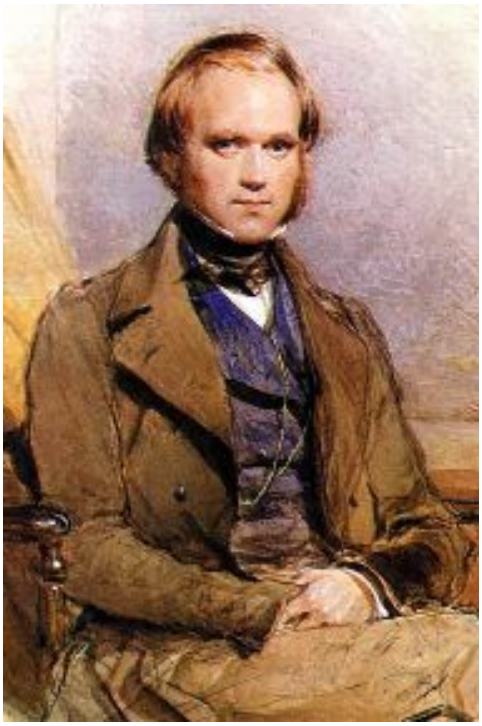

Figure 12.8: Darwin's writings on geology and the collections of plants, animals, and fossils he sent back to England established his reputation as a naturalist even before he returned from his voyage. After his return, his father supported him as a "gentleman scientist," allowing him to further develop the ideas inspired by his travels.

Standing on the Shoulders of Giants

Science, like evolution, builds on the past. Darwin's theory was a product not only of his own intellect, but also of the times in which he lived and the ideas of earlier great thinkers. Some of these ideas colored Darwin's perspective during his five years on the *Beagle;* many contributed to his thinking after the voyage. Not until 23 years after he returned to England did Darwin crystallize his thoughts and evidence sufficiently to publish his theory.

Before Darwin, most people believed that all species were created at the same time and remained unchanged throughout history. History, they thought, reached back just 6,000 years.

One of the first scientists to explore change in species was Jean Baptiste Lamarck. Lamarck believed that organisms improve traits through increased use, and then pass the improved feature on to their offspring. According to this idea of **inheritance of acquired characteristics**, giraffes have long necks because early giraffes stretched their necks to reach tall trees and then passed the longer necks on to their calves, as shown in **Figure** 12.9. This attempt to explain adaptation was popular during the 19th century, and undoubtedly influenced Darwin's thinking. Although Lamarck advanced the proposal that species change, evidence does not support inheritance of acquired characteristics. You can weight-train for years, but unless your children train as hard as you did, their muscles will never match yours! We will look later at Darwin's explanation for giraffes' necks.

Much as Lamarck questioned the dogma that species do not change, Charles Lyell challenged the belief that the earth was young. In *Principles of Geology,* he recorded detailed observations of rocks and fossils, and used present patterns and processes as keys to past events. He concluded that many small changes over long periods of time built today's landscapes, and that the earth must be far older than most people believed. Captain FitzRoy gave Darwin a copy of *Principles of Geology* just before the *Beagle* left England, and Darwin "saw through [Lyell's] eyes" during the voyage. Darwin's theory that present species developed gradually over long periods of time reflects Lyell's influence.

The idea that natural laws, rather than miracles, govern life as well as geology grew during the early 19th century. Charles Babbage wrote that God had the power to make laws, which in time produce species. His close friend, John Herschel, called for a search for natural laws underlying the "mystery of mysteries" of how species formed. Later, Darwin cited Herschel as "one of our greatest philosophers" and then said he intended "to throw some light on the origin of species — that mystery of mysteries."

Darwin's idea that individuals in a population compete for resources came from reading Thomas Malthus. Malthus described a human "struggle for existence" due to exponential population growth and limited food. Darwin thought that animal and plant populations might have similarly limited resources. If so, offspring suited to their environment would be more likely to survive, while those less "fit" would perish.

Breeders of pigeons, dogs, and cattle inspired Darwin's ideas about selection. By choosing

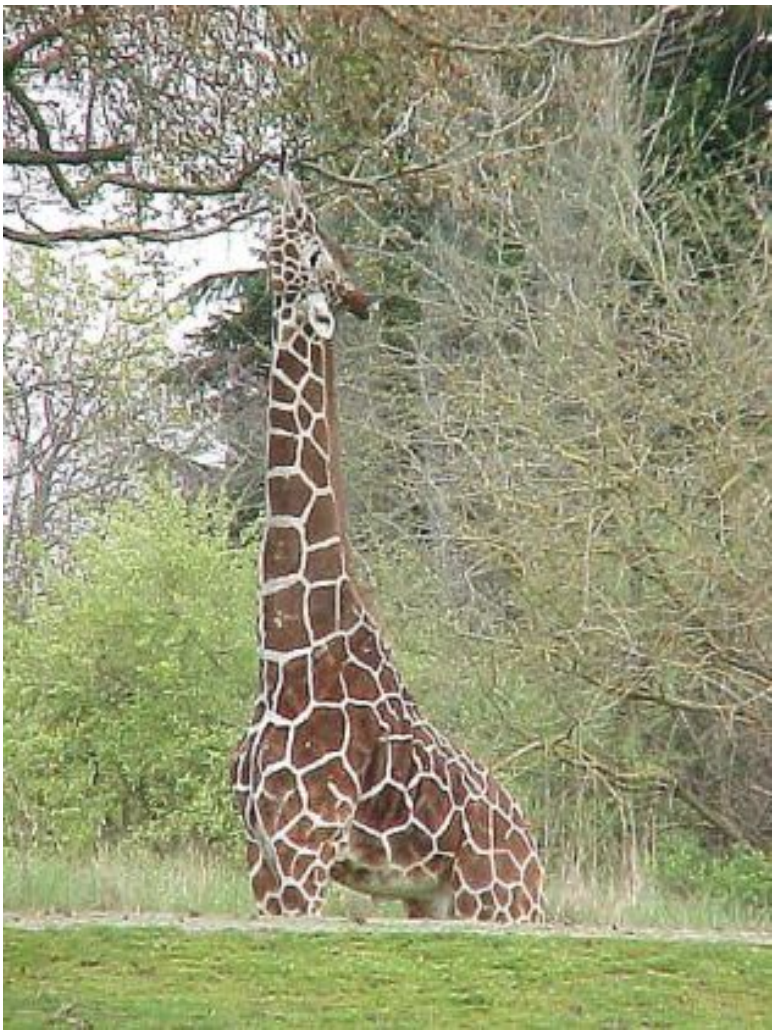

Figure 12.9: According to Lamarck's idea, inheritance of acquired characteristics, giraffes have long necks because earlier giraffes stretched their necks to reach tall trees, and then passed their lengthened necks down to their calves. Evidence does not support this hypothesis, but many credit Lamarck for advancing the idea that species develop and change.

which animals reproduced, breeders could achieve remarkable changes and diversity in a relatively short time. Variations in traits were clearly abundant and heritable. Darwin referred to selective breeding as **artificial selection**. His observations of how artificial selection worked helped him to develop his concept of **natural selection** (**Figure** 12.10).

Figure 12.10: The way in which animal breeding artificially selects desirable variations influenced Darwin's ideas of natural selection. The English Carrier Pigeon (left), the English Fantail (center), and the Fiary Swallow (right) have all "descended" from the common rock pigeon (), with the help of human breeders.

One of the last individuals to influence Darwin's theory was Alfred Russel Wallace, a naturalist whose work in Malaysia led him to conclusions similar to Darwin's. In 1858 - over 20 years since the *Beagle* returned to England - Wallace sent Darwin a paper which described concepts nearly identical to Darwin's ideas about evolution and natural selection. Lyell helped arrange a joint presentation to the Linnean society two weeks later. Darwin, shocked by the sudden competition, worked quickly to complete his book by the following year. Although both naturalists had independently come to the same conclusions, the extensive evidence and careful logic Darwin presented in *The Origin of the Species* earned him the greater share of recognition for the theory of evolution by natural selection.

Standing on the shoulders of the giants who went before him, Darwin was able to see past the countless details of his beloved work in natural history to formulate a unifying theory to explain the diversity of life.

Darwin's Theory of Evolution

Darwin lived in an increasingly scientific society which had begun to accept the idea that universal "laws" governed processes in nature - perhaps including life itself. Like Lamarck, Darwin understood that species change. With Lyell, he saw that the history of Earth and its life covered a vast amount of time. From his observations of animal breeding, he recognized that even within species, individuals showed variation in traits, and that the variations could be passed to offspring. Recalling Malthus, he knew that populations could produce far more offspring than the environment could support. He predicted that individuals with traits which suited the environment would survive and reproduce to pass their favorable traits to offspring, as shown in **Figure** 12.11. Those whose traits were less suited to the

environment would die. Just as humans select for breeding those cattle which produce more milk, he reasoned, nature (the limited environment) selects individuals which use resources most efficiently. Thus, he called his explanation of how species change *natural selection.*

Darwin defined natural selection as the "principle by which each slight variation [of a trait], if useful, is preserved," and he later regretted that he had not named it "natural preservation." Today it is often defined as the process by which a certain trait becomes more common within a population. Let's look once more at the parts of this process, and then we will consider its consequences.

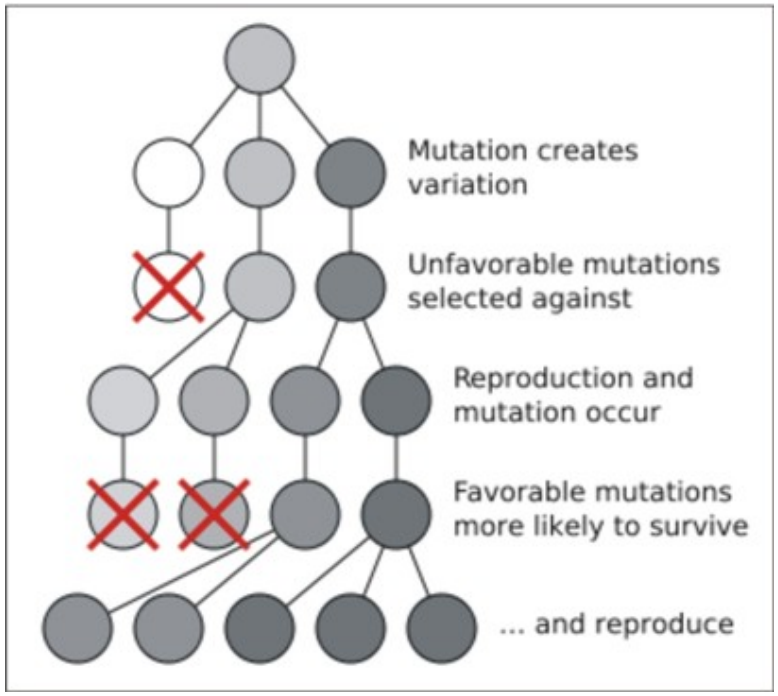

Figure 12.11: Natural selection involves heritable variation, overproduction of offspring, preferential survival of individuals having variations favorable for the environment, and reproduction by survivors. This diagram shows two selection events, with reproduction after each one.

By chance, heritable variations exist within a species.

Darwin did not know that genes made of DNA determine traits. Much later, scientists learned that mutations in DNA can change genes and produce variations in traits. However, his observations of animal breeding and his detailed studies of barnacles and orchids convinced him that small, heritable variations in traits were common among individuals within a species. Darwin probably recognized that sexual reproduction increased variety in offspring. He expressed considerable concern that his own health problems might be heritable,

especially when his beloved daughter Annie grew ill and died. He believed that his marriage to his cousin may have contributed to his children's weaknesses.

Species produce more offspring than can survive.

Malthus argued that human populations grow exponentially if unchecked, but that disease, starvation, or war will limit population growth eventually. High birth rates and high death rates were characteristic of human history. Darwin himself had ten children; three died before maturity. Darwin reasoned that all species had the capacity to grow. However, his observations showed that most populations remained stable due to environmental limits. He concluded that many offspring must die. The phrases ***overproduction of offspring*** and ***struggle for existence*** summarize this idea.

Offspring with favorable variations are more likely to survive to reproduce.

Although heritable variations appeared to be random, death, Darwin reasoned, was not. Offspring which, *by chance*, had variations which "fit" or adapted them to their environment would have a greater chance to survive to maturity and a greater chance to reproduce. Offspring without such adaptations were more likely to die. Thus, well-adapted individuals produce more offspring. ***Differential survival and reproduction*** is a cornerstone of natural selection.

Gradually, individuals with favorable variations make up more of the population.

Can an individual organism evolve? No. The accomodation of an individual organism to its environment is not evolution. Though an individual organism can be better adapted to its environment, it still must mate with others of its species, so by definition, it is not a new species. It is just an individual with a better chance of survival in its environment. It is the gradual accumulation of many adaptations that, over many generations within one lineage of organisms, results in a new species. These adaptations occur through genetic change.

Through chance variation, overproduction of offspring, and differential survival and reproduction, the proportion of individuals with a favorable trait (or favorable phenotype) will increase. The result is a population of individuals adapted to their environment. It is the variation within a species that increases the likelihood that at least some members of a species will be adapted to their environment and survive under changed conditions.

It is important to note that natural selection is *not* directed or intentional. It depends on chance variations - due to genetic variations - and can work only with the "raw material"

of existing species. Occasionally, variations which have no particular adaptive logic may survive. However, the limits set by resources and environment usually mean an increase in traits which help survival or reproduction, and the loss of traits which harm them. Gradually, ***species change***. Eventually, changes accumulate and a new species is formed.

Let's compare natural selection to inheritance of acquired characteristics (Lamarck's idea mentioned above). How would Darwin's mechanism explain the long necks of giraffes?

1. ***Heritable variation***: In the past, some giraffes had short necks, and some had long necks.
2. ***Overproduction of offspring***: Giraffes produced more young than the trees in their environment could support.
3. ***Differential survival and reproduction***: Because the long-necked giraffes could feed from taller trees, they were more likely to survive and produce more offspring. Short-necked giraffes were more likely to starve before they could reproduce.
4. ***Species change***: The long-necked giraffes passed their long necks on to their calves, so that each generation, the population contained more long-necked giraffes.

Recall that Lamarck believed that giraffes could stretch their necks to reach tall trees, and pass their stretched necks on to offspring. If this were true, evolution would reward effort toward a goal. Darwin showed that evolution is not goal-directed. Instead, the environment reinforces variations which occur by chance.

Lyell studied the geology which surrounded him and saw that the environment had changed many times over a vast amount of time. Darwin studied the life across continents and saw, in addition to tremendous variation, that species had changed – in response to the changes in their environment – over that vast amount of time. Both proved, with careful observations and well-reasoned inferences, that the present arises from the past. Limited to our brief lifespans, we see today's species as fixed. Darwin taught us how to see the relationships between them; to see that they developed from earlier, distinctly different species; to see that all of them - all of *us* - share common ancestors (**Figure** 12.12). The cartoons which showed Darwin as an ape (an example is shown in the next lesson) did a great disservice to his theory of evolution. Far too many people limit their understanding of evolution to the simple phrase that "we came from apes." We humans share common ancestors not only with the great apes, but with ALL of life – blue whales, gazelles, redwood trees, saguaros, fireflies, mosquitoes, puffballs, amebas, and bacteria. As Darwin said in closing the *Origin*, "There is grandeur in this view of life."

Darwin delighted in the great diversity of life, but also saw unity within that diversity. He saw striking patterns in the similarities and differences. Seeking an explanation for those patterns, he developed the concept of natural selection. Natural selection explains how today's organisms could be related – through "descent with modification" from common ancestors. Natural selection explains the story told by the fossil record – the long history of

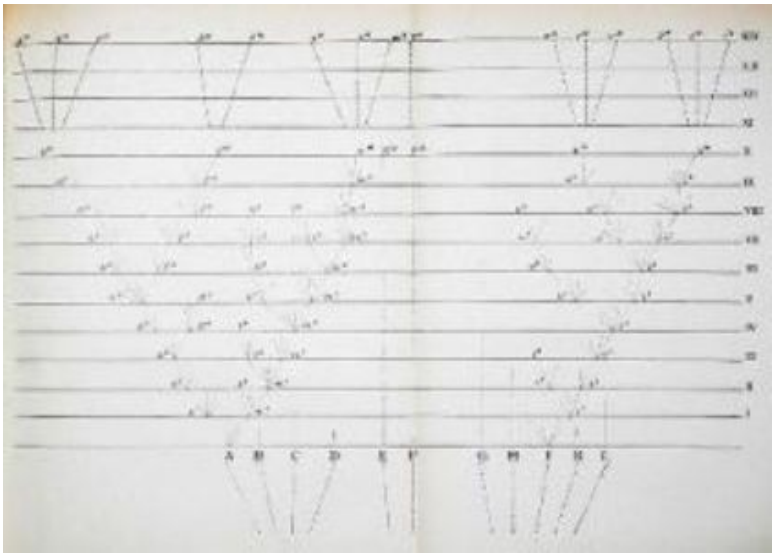

Figure 12.12: A sketch from Darwin's this "Tree of Life" depicts his ideas of how today's species (top row, XIV) have descended with modification from common ancestors. The theory implies that all species living today have a universal common ancestor – that we humans are related to all of Earth's plants, animals, and microorganisms.

life on Earth. Natural selection is a scientific answer (if only partial) to the old questions: Who are we? How did we come to be?

In the light of natural selection, it is easy to see that variation – differences among individuals within a population – increases the chance that at least some individuals will survive if the environment changes. Here is a strong argument against cloning humans: if we were all genetically identical – if variation (or genetic variation) did not exist – a virus which previously could kill just some of us would either kill all of us, or none of us. Throughout the long history of life, variation has provided insurance that inevitable changes in the environmental will not mean the extinction of a species. Similarly, the diversity of species ensures that environmental change will not mean the extinction of life. Life has evolved (or, the Earth's changing environment has selected) variation and diversity because they ensure survival. Causes of mutation may have pre-existed, but in a sense, life has embraced them. And sexual reproduction has evolved to add further to variation and diversity (as discussed in the *Cell Division and Reproduction* chapter).

Adaptations are logical because the environment imposes limits on organisms, selecting against those who do not "fit." Adaptations arise through gradual accumulation of chance variations, so they cannot be predicted, despite the fact that they appear to be goal-directed or intentional. Adaptations relate to every aspect of life: food, water, oxygen, nutrients, shelter, growth, response, reproduction, movement, behavior, ability to learn. Adaptations connect organisms to the resources in their environments. You are born with your adaptations; they are not changes you make to fit yourself into an environment. If the environment

changes, the adaptive value of some of your inherited characteristics may also change. Our human appetites for salt and fat, for example, may remain from our past, when fat and salt were rare in our environment; now that they are easily available, we consume more than is good for us. Biologist E.O. Wilson believes adaptations reach every aspect of human life - that social, political, and even religious behaviors are rooted in our genes. Of course, we can learn – and learning allows us to adapt within our lifetimes to environmental change. The ability to learn is itself an adaptation – perhaps our greatest gift. But more and more, we are discovering that much of our behavior – including learning - is genetically programmed – a gift from our ancestors similar to vision and hearing, or breathing and digestion.

Darwin's theory can be summarized in two statements All living species share common ancestors, and
Natural selection explains how species change.

In this lesson, we have explored Darwin's reasoning. In the next lesson, we will consider the abundant evidence which supports his ideas.

Lesson Summary

- The Theory of Evolution has changed how we see ourselves and how we relate to our world.
- The theory has two basic ideas: the common ancestry of all life, and natural selection.

- Darwin studied medicine and theology, but he first worked as ship's naturalist on the HMS *Beagle*.
- During the 5-year voyage, Darwin spent over 3 years on land exploring new rocks, fossils, and species.
- From his observations, Darwin developed new ideas which later formed the foundation of his theory.

1. Rock and fossil formations suggested that continents and oceans had changed dramatically.
2. Tropical rain forests encouraged Darwin to reconsider the source of the vast diversity of life.
3. Native cultures raised questions about the relationship between humans and animals.
4. Sedimentary rocks implied gradual, as opposed to catastrophic, changes in the earth and in life.
5. The distribution of life on island chains challenged the dogma of the immutability of species.

- After he returned, his reputation as a naturalist and his father's financial support allowed him to become a "gentleman scientist," free to analyze his collections, formulate his theory, and write about both.

- Like all scientific theories, Darwin's was a product of both his own work and the work of other scientists.
- Before Darwin, most people believed that all species were created and unchanging about 6000 years ago.
- Jean-Baptiste Lamarck proposed that acquired characteristics could be inherited. Evidence did not support his mechanism for change, but Darwin shared his ideas of change in species.
- Charles Lyell wrote that present rock formations have developed through gradual changes over long periods of time. Darwin applied his ideas to present life forms.
- Observations of animal breeding helped Darwin appreciate the importance of heritable variations.
- Malthus' work showed that populations produce more offspring than the environment can support.
- Charles Babbage and John Herschel believed that natural laws governed the origin of species.
- Alfred Russel Wallace formulated a theory very similar to Darwin's. Although they collaborated on a joint paper, Darwin's clear and forceful *Origin of Species* earned him greater credit.

- The two general ideas of Darwin's Theory are evolution and natural selection.
- The concept of natural selection includes these observations and conclusions:

1. By chance, heritable variations exist within a species.
2. Species produce more offspring than can survive.
3. Offspring with favorable variations are more likely to survive to reproduce.
4. Gradually, individuals with favorable variations make up more of the population.

- Variation among individuals within species ensures that some will survive environmental change.
- Because some variations help survival in a specific habitat more than others, individuals having those variations are more likely to survive and reproduce.
- This differential survival and reproduction results in a population which is adapted to its environment.
- The result of natural selection is gradual change in species, and when enough changes have accumulated, new species form. This is "descent with modification."
- The idea that natural selection has led to the origin of all species, together with evidence from the fossil record, means that all existing species are related by "common ancestry."
- Evolution by natural selection explains the history of life as recorded in the fossil record.
- Common ancestry explains the similarities, and natural selection in the face of environmental change explains the differences among present-day species.
- Like Lyell's Principles of Geology, Darwin's Theory of Evolution supports the general principle that the present arises from the materials and forms of the past.

Review Questions

1. State 3 of the 5 ideas Darwin developed during the Voyage of the Beagle. For each idea, give and example of a specific observation he made which supports the idea.
2. Compare and contrast Darwin's position as a "gentleman scientist" with today's professional scientists.
3. What does the expression "standing on the shoulders of giants" say about Darwin and his Theory of Evolution? Support your interpretation with at least three specific examples.
4. Explain the importance of Lyell's Principles of Geology to Darwin's work.
5. Discuss the influence of animal breeding on Darwin's thinking.
6. Clarify the relationship between Darwin and Alfred Russel Wallace.
7. Summarize in your own words the two basic ideas which make up Darwin's Theory of Evolution.
8. Compare and contrast Lamarck's and Darwin's ideas using the evolution of the human brain as an example.
9. Why is it incorrect to say that evolution means organisms adapt to environmental change?
10. Why is it not correct to say that evolution means "we came from monkeys?"

Further Reading / Supplemental Links

- http://www.aboutdarwin.com/voyage/voyage03.html
- http://darwin-online.org.uk/
- http://www.ucmp.berkeley.edu/history/evolution.html
- http://www.pbs.org/wgbh/evolution/
- http://www.literature.org/authors/darwin-charles/the-origin-of-species/
- http://www.life.umd.edu/emeritus/reveal/pbio/darwin/darwindex.html

Vocabulary

adaptation A characteristic which helps an organism survive in a specific habitat.

artificial selection Animal or plant breeding; artificially choosing which individuals will reproduce according to desirable traits.

inheritance of acquired characteristics The idea that organisms can increase the size or improve the function of a characteristic through use, and then pass the improved trait on to offspring.

law A statement which reliably describes a certain set of observations in nature; usually testable.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

theory An explanation which ties together or unifies a large group of observations.

Points to Consider

- How might the Theory of Evolution help us to understand and fight disease?
- What other aspects of medicine could benefit from an understanding of evolution?
- How can evolution and natural selection improve conservation of species and their environments?
- How would you put into words the ways in which evolution has changed the way we look at ourselves?
- How do you think it has altered the way we relate to other species? To the Earth?
- Consider the human brain. If Lamarck's hypothesis about inheritance of acquired characteristics were true, how would your knowledge compare to your parents?

12.2 Lesson 12.2: Evidence for Evolution

Lesson Objectives

- Clarify the significance of a scientific theory.
- Recognize that Darwin supported his theory with a great deal of evidence, and that many kinds of evidence since his time have further strengthened the theory of evolution.
- Describe how Darwin used the fossil record to support descent from common ancestors.
- Compare and contrast homologous structures and analogous structures as evidence for evolution.
- Give examples of evidence from embryology which supports common ancestry.
- Explain how vestigial structures support evolution by natural selection.
- Discuss the molecular similarities found in all species of organisms.
- Describe how evolution explains the remarkable molecular similarities among diverse species.
- Analyze the relationship between Darwin's Theory of Evolution and more recent discoveries such as Mendel's work in genetics and the molecular biology of DNA and protein.
- Relate the distribution of plants and animals to changes in geography and climate.
- Explain how biogeography supports the theory of evolution by natural selection.
- Summarize the explanation given by both Darwin and Wallace for the distribution of few, closely related species across island chains.

Introduction

You are probably aware that the concept of evolution still generates controversy today, despite its wide acceptance. In *The Origin of the Species*, Darwin mentioned humans only once, predicting, "Light will be thrown on the origin of man and his history." Nevertheless, some people immediately distorted its far-reaching message about the unity of life into near-sighted shorthand: humans "came from" monkeys (**Figure** 12.13).

Figure 12.13: In Darwin's time and today, many people incorrectly believe that evolution means "humans come from monkeys." This interpretation does not do justice to Darwin's theory, which holds that all species share common ancestry.

In the last lesson, you learned that evolution relates all of life – not just humans and monkeys. In this lesson, you will learn that biological evolution, like all scientific theories, is much more than just an opinion or **hypothesis**, it is based on evidence.

In science, a **theory** is an explanation which ties together or unifies a large group of observations. Scientists accept theories if they have a great deal of supporting evidence. In *The Origin of the Species,* Darwin took the time to compile massive amounts of fossil and biological evidence to support his ideas of natural selection and descent from common ancestors. He clearly and effectively compared animal breeding (artificial selection), which was familiar to most people, and natural selection. Because Darwin provided so much evidence and used careful logic, most scientists readily accepted natural selection as a mechanism for

change in species. Since Darwin's time, additional fossil and biological data and new fields of biology such as genetics, molecular biology, and biogeography have dramatically confirmed evolution as a unifying theory – so much so that eminent biologist Theodosius Dobzhansky wrote that "Nothing in biology makes sense except in the light of evolution."

In this lesson, you can explore and evaluate for yourself the many kinds of evidence which support the theory of evolution by natural selection. You will also have the opportunity to appreciate the power of evolution to explain observations in every branch of biology.

The Fossil Record: Structural Changes Through Time

Few would argue that dinosaurs roamed Earth in the past, but no longer exist. The **fossil record** is a revealing window into species that lived long ago. **Paleontologists** have carefully analyzed the preserved remains and traces of animals, plants, and even microorganisms to reconstruct the history of life on Earth (see the *History of Life* chapter for more detail). **Relative** (rock layer position) and **absolute (radioisotope) dating** techniques allow geologists to sequence the **fossils** chronologically and provide a time scale. Geology also reveals the environmental conditions of past species.

For many reasons, the fossil record is not complete. Most organisms decomposed or were eaten by scavengers after death. Many species lacked hard parts, which are much more likely to fossilize. Some rocks and the fossils they contained have eroded and disappeared. Moreover, much of evolution happens in the small populations that survive changes in environmental conditions, so the chance that intermediates will fossilize is low. Nevertheless, the current record includes billions of fossils – over 300 million from Los Angeles' LaBrea Tar Pits alone, and an estimated 800 billion in South Africa's Beaufort Formation. Analysts have identified 250,000 species among these remains.

Although the fossil record is far more detailed today than in Darwin's time, Darwin was able to use it as powerful evidence for natural selection and common descent. Throughout geological history, species that appear in an early rock layer disappear in a more recent layer. Darwin argued that a species' appearance recorded its origin, and that its disappearance showed extinction. Moreover, he noted remarkable similarities among structures in differing species, supporting common ancestry. Finally, he could often correlate environmental conditions with structures, supporting his idea that natural selection led to adaptations which improved survival within certain habitats.

As an example, let's analyze a relatively complete set of fossils which record the evolution of the modern horse. **Figure** 12.14 sequences five species which show major evolutionary changes. The oldest fossil shows a fox-sized animal with slender legs and nearly vertical digits: *Hyracotherium* bit and chewed soft leaves in wooded marshlands. Geology and paleontology suggest that the climate gradually dried, and grasslands slowly replaced the marshes. *Mesohippus* was taller, with fewer, stronger digits – better able to spot and run from predators, and thus more likely to survive and reproduce in the new grasslands. *Merychippus* was taller

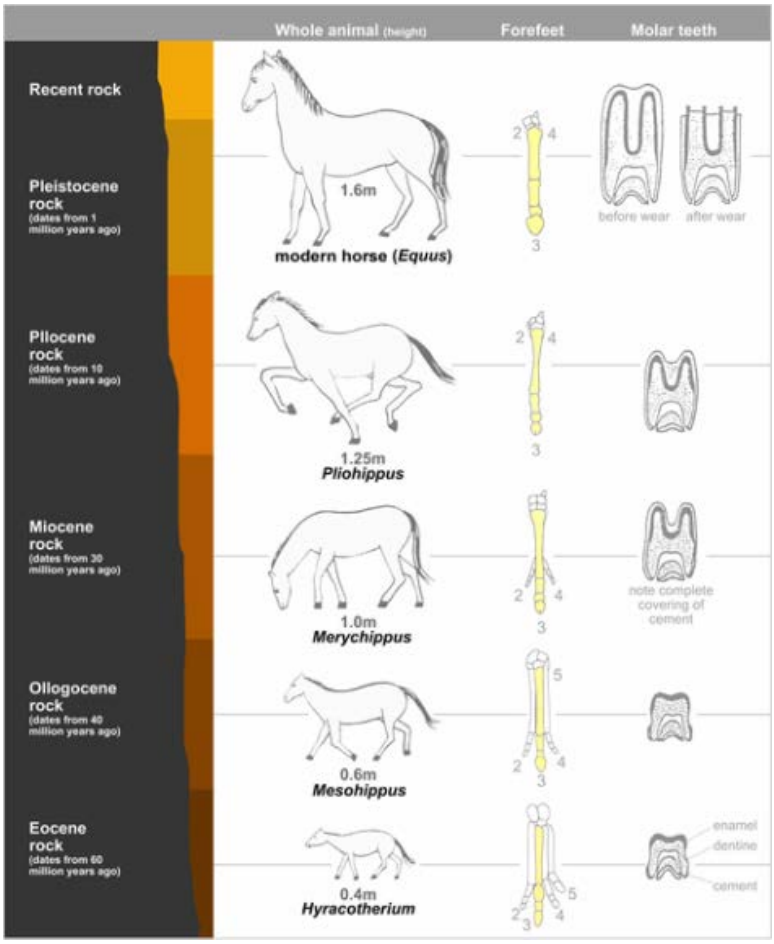

Figure 12.14: The fossil record for relatives of the modern horse is unusually complete, allowing us to select a few which show major change over time. These changes can be correlated with environmental changes, supporting the ideas of evolution and natural selection. However, the linear arrangement is misleading; addition of all known fossils would show a branching, bushy path of descent and common ancestry.

still, and kept only one, enlarged digit – a hoof to run fast on the hard ground. By *Pliohippus* time, molar teeth had widened and elongated to grind the tough grasses. These fossils show gradual structural changes which correspond to changes in the environment. They appear to show a smooth, linear path directed toward the "goal" of the modern horse, but this is deceiving. These five fossils are merely "snapshots" of a bushy family tree containing as many as 12 genera and several hundred species. Some transitions are smooth progressions; others are abrupt. Together, they support natural selection and descent with modification from common ancestors.

Comparative Anatomy and Embryology

The evidence Darwin presented in *The Origin of Species* included not only fossils but also detailed comparisons of living species at all life stages. Naturalists in Darwin's time were experts in **comparative anatomy** – the study of the similarities and differences in organisms' structures (body parts). At different times during his life, Darwin studied the comparative anatomy of closely related species of marine mammals, barnacles, orchids, insectivorous plants, and earthworms.

Species which share many similarities are closely related by a relatively recent common ancestor. For example, all orchids share parallel-veined leaves, two-sided flowers with a "lip," and small seeds (**Figures A and B** 12.15). Species which share fewer similarities, sharing only basic features, are related by relatively distant ancestor. The sundew, one of the insectivorous plants Darwin studied, shares leaves and petals with orchids, but the leaves are wide with branching veins and the flowers are radially symmetrical rather than two-sided (**Figure C** 12.15). The many species of orchids, then, share a recent common ancestor, but they also share a more distant ancestor with the sundew.

Homologous and Analogous Structures

Similarities can show two different kinds of relationships, both of which support evolution and natural selection.

(1) Similarities shared by closely related species (species who share many characteristics) are **homologous**, because the species have descended from a common ancestor which had that trait. Homologous structures may or may not serve the same function. **Figure** 12.16 shows the forelimbs of mammals, considered homologous because all mammals show the same basic pattern: a single proximal bone joins a pair of more distal bones, which connect to bones of the wrist, "hand," and digits. With this basic pattern, bats build wings for their lives in the air, whales form fins for their lives in the sea, and horses, as we have seen, construct long, hoofed legs for speed on land. Therefore, homologous structures support common ancestry.

(2) Similarities shared by distantly related species may have evolved separately because they live in similar habitats. These structures are **analogous** because they serve similar functions,

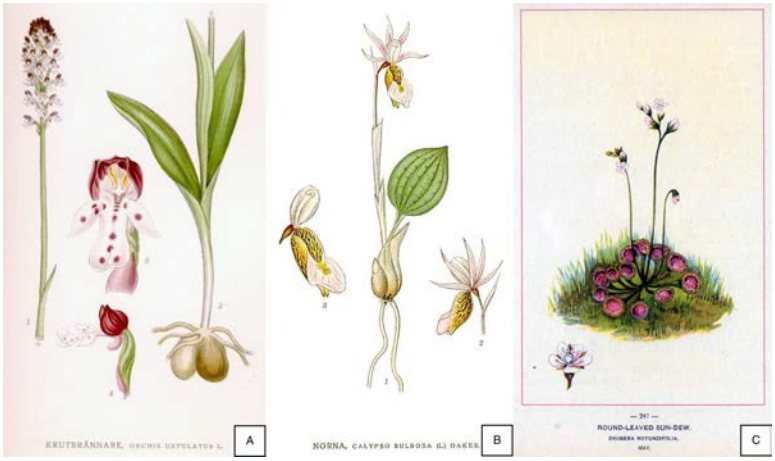

Figure 12.15: Darwin's Theory of Evolution explains both the similarities and the differences among living things. All flowering plants share leaves, petals, stamens, and pistil, but orchids have parallel-veined leaves and flowers with lips and fused stamens and pistil, while sundews have leaves with branching veins and flowers with equal petals and separate stamens and pistil. The two species of orchid (A and B) share a recent common ancestor, whereas all three species share a more distant common ancestor.

but evolved independently. **Figure** 12.17 compares the wings of bats, bird, and pterosaurs. Bats evolved wings as mammals, pterosaurs as dinosaurs, and birds from a separate line of reptiles. Their wings are analogous structures, each of which evolved independently, but all of which suit a lifestyle in the air. Note that although the wings are analogous, their bones are homologous: all three share a common but more distant vertebrate ancestor, in which the basic forelimb pattern evolved. Because analogous structures are independent adaptations to a common environment, they support natural selection.

Embryology

Embryology is a branch of comparative anatomy which studies the development of vertebrate animals before birth or hatching. Like adults, embryos show similarities which can support common ancestry. For example, all vertebrate embryos have gill slits and tails, shown in **Figure** 12.18. The "gill slits" are not gills, however. They connect the throat to the outside early in development, but in many species, later close; only in fish and larval amphibians do they contribute to the development of gills. In mammals, the tissue between the first gill slits forms part of the lower jaw and the bones of the inner ear. The embryonic tail does not develop into a tail in all species; in humans, it is reduced during development to the coccyx, or tailbone. Similar structures during development support common ancestry.

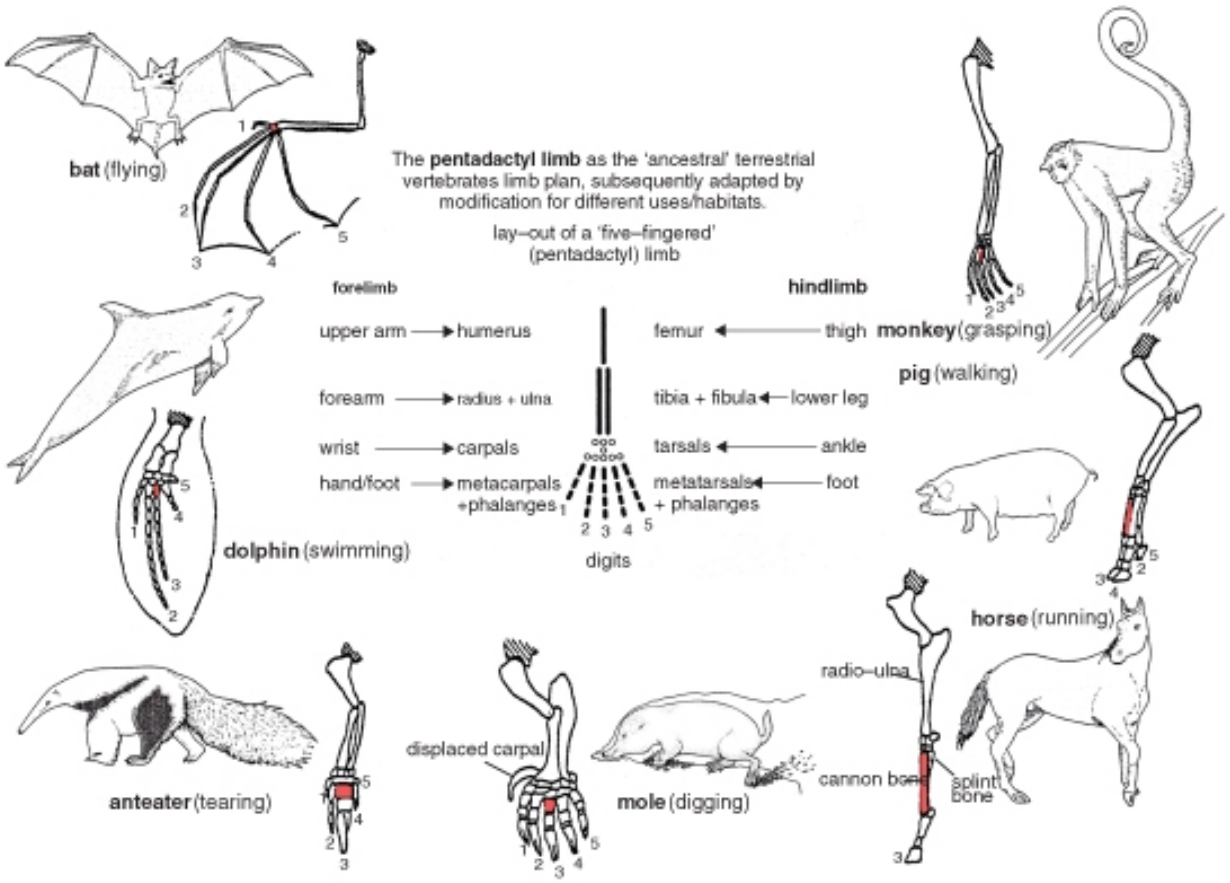

Figure 12.16: are similarities throughout a group of closely related species. The similar bone patterns in bat's wings, dolphin's flippers, and horse's legs support their descent from a common mammalian ancestor.

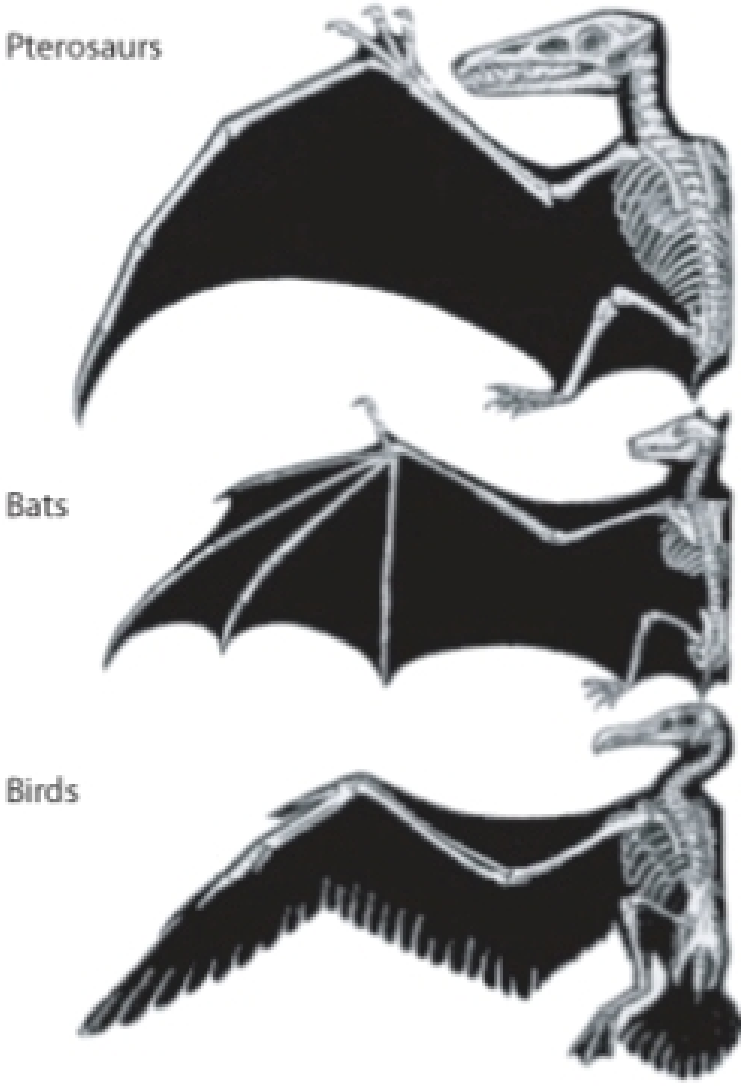

Figure 12.17: The wings of pterosaurs, bats, and birds illustrate both homologous and analogous structures. Similarities in the patterns of bones are due to descent from a common vertebrate (reptilian) ancestor, so they are homologous. However, the wings of each evolved independently, in response to similar environments, so they are analogous, and provide evidence for natural selection.

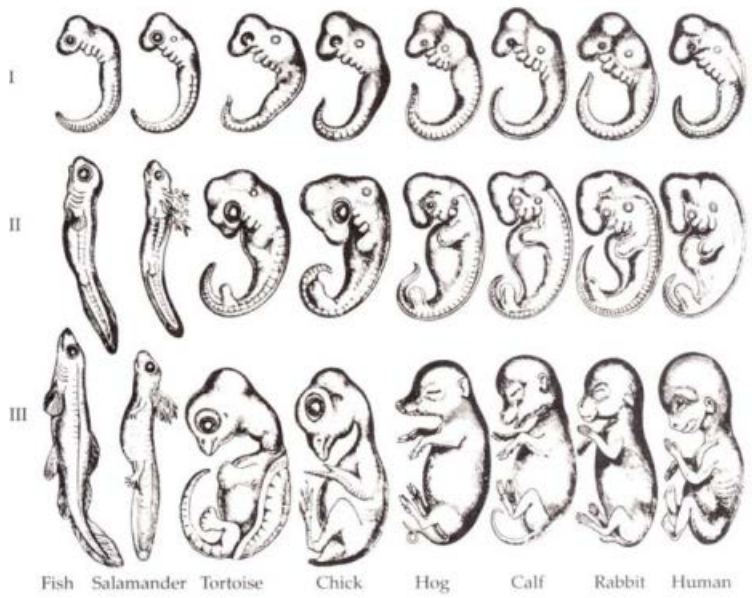

Figure 12.18: reveals homologies which form during development but may later disappear. All vertebrate embryos develop tails, though adult humans retain only the coccyx. All vertebrate embryos show gill slits, though these develop into gill openings only in fish and larval amphibians. In humans, gills slits form the lower jaw and Eustachian tube. Many scientists consider developmental homologies evidence for ancestry, although some embryologists believe that these particular drawings exaggerate the similarities.

Vestigial Structures

Structures which are reduced and perhaps even nonfunctional, such as the human tail and the human appendix, are considered **vestigial structures**. The tail, of course, functions for balance in many mammals, and the human appendix may have served digestive functions in herbivorous ancestors. Whales, which evolved from land mammals, do not have legs or hair as adults; both begin to develop in embryos, but then recede. Vestigial leg bones remain, buried deep in their bodies, shown in **Figure A** 12.19.

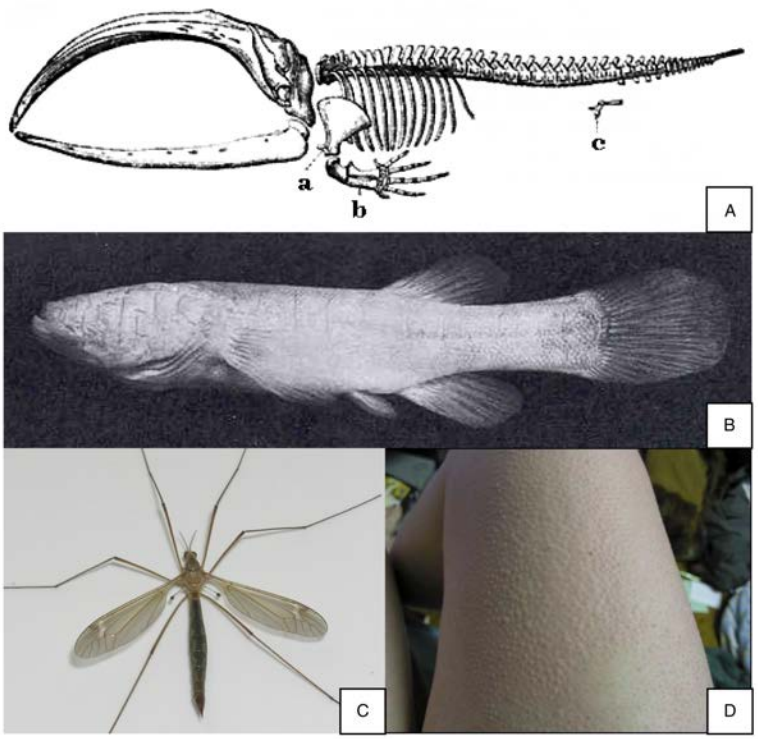

Figure 12.19: Vestigial structures show evolutionary reduction or loss of unneeded structures which were useful to ancestors. A: Whales retain remnants of their mammalian ancestors' leg bones (c). B: Cavefish lack the eyes and pigments important to their relatives who live in lighted habitats. C: True flies have reduced insects' second pairs of wings to balancing knobs. D: We still show the reflex which raises hairs for insulation in cold air in our furry relatives, but all we have to show for our follicle's efforts are goosebumps.

True flies have reduced the second pair of wings found in most insects to halteres for balance shown in **Figure B** 12.19. Cavefish lose both eyes and pigment, because both would require energy to build and are useless in the lightless habitat they have adopted shown in **Figure C** 12.19. You are probably very familiar with a fine example of a vestigial behavior: goosebumps raise the sparse hairs on your arms even though they are no longer sufficiently dense to insulate you from the cold by trapping warm air next to your skin; in most mammals, this reflex is still quite functional shown in **Figure D** 12.19. Most vestigial structures are

homologous to similar, functioning structures in closely related species, and as such, support both common ancestry and (incomplete!) natural selection.

Molecular Biology

Did you know that your genes may be 50% the same as those of a banana?

Unknown in Darwin's time, the "comparative anatomy" of the molecules which make up life has added an even more convincing set of homologies to the evidence for evolution. All living organisms have genes made of DNA. The order of nucleotides – As, Ts, Cs, and Gs - in each gene codes for a protein, which does the work or builds the structures of life. Proteins govern the traits chosen (or not) in natural selection. For all organisms, a single Genetic Code translates the sequence of nucleotides in a gene into a corresponding chain of 20 amino acids. By itself, the universality of DNA genes and their code for proteins is strong evidence for common ancestry. Yet there is more.

If we compare the sequence of nucleotides in the DNA of one organism to the sequence in another, we see remarkable similarities. For example, human DNA sequences are 98-99% the same as those of chimpanzees, and 50% the same as a banana's! These similarities reflect similar metabolism. All organisms have genes for DNA replication, protein synthesis, and processes such as cellular respiration. Although metabolic processes do not leave fossils, similar DNA sequences among existing organisms provide excellent evidence for common ancestry.

The *differences* in DNA sequences are even more intriguing. Many are single base substitutions resulting from mutations accumulated through time. Assuming mutations occur randomly, the number of differences in bases between any two species measures the time elapsed since two organisms shared a common ancestor. This type of "molecular clock" has confirmed traditional classification based on anatomy. Most scientists consider it sufficiently powerful to clarify or correct our understanding of evolutionary history. For example, human DNA differs 1.2% from chimpanzees, 1.6% from gorillas, and 6.6% from baboons; we can infer from this data that humans and chimpanzees share a relatively recent common ancestor, and that the common ancestor we share with gorillas lived much longer ago. **Figure** 12.20 shows a **cladogram** depicting hypothetical evolutionary relationships constructed with this data. Similarities and differences in the sequences of amino acids in proteins support common ancestry in the same way, because they are determined by DNA.

Heritability and variation in traits are essential parts of Darwin's theory of evolution by natural selection. Since he published *The Origin of the Species,* rediscovery of Mendel's identification of genes and how they are inherited has confirmed Darwin's ideas. Molecular biology has clarified the nature of genes and the sources of variation. Comparative analysis of DNA and proteins continues to give us an exquisitely detailed view of patterns of variation, common ancestry, and how evolution works.

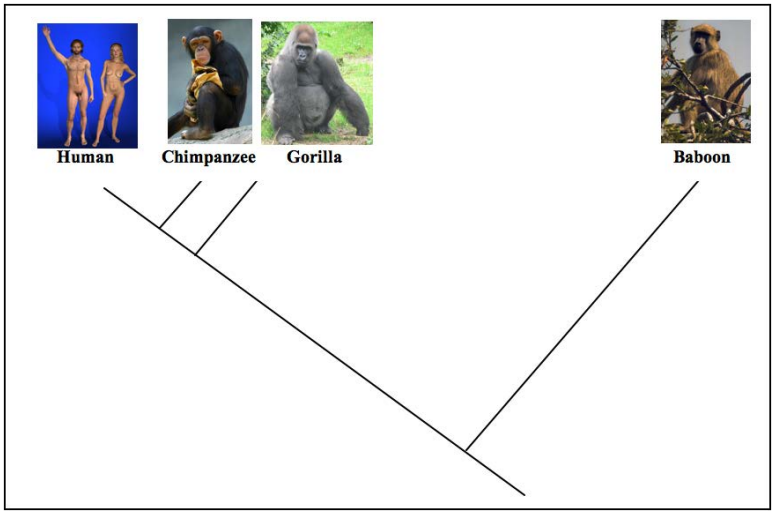

Figure 12.20: Cladograms use comparison data to construct diagrams showing evolutionary relationships. This cladogram uses comparisons of DNA nucleotide sequences to reveal patterns of descent from common ancestors. Molecular biology has supported and extended our understanding of evolutionary relationships based on traditional anatomy.

Biogeography

Australia, Africa, and South America occupy the same latitude, at least in part, and therefore have roughly the same climate. If plants and animals were distributed only according to their adaptations to habitat, we would expect the same species to occupy similar regions of these continents. However, the short-tailed monkeys, elephants, and lions in Africa differ significantly from the long-tailed monkeys, llamas, and jaguars of South America, and even more from the koalas, kangaroos, and Tasmanian devils of Australia. **Biogeography** studies the distribution of plants and animals and the processes that influence their distribution – including evolution and natural selection. Only geologic change and evolution can explain the distributions of many species, so biogeography is another kind of evidence for the theory of evolution.

Alfred Russel Wallace, who developed his own ideas of evolution and natural selection at the same time as Darwin, explained the distributions of many species in terms of changes in geography (such as formation of land bridges) and environment (for example, glaciations) and corresponding evolution of species. **Figure** 12.21 shows the six biogeographical regions he identified: Nearctic, Neotropical, Palaearctic, Ethiopian, Oriental, and Australian.

Let's consider just the camel family as an example, shown in **Figure** 12.22 of how biogeography explains the distribution of species. Fossils suggest that camel ancestors originated in North America. Distant fossils show structural similarities which suggest that their descendants migrated across the Bering land bridge to Asia and across the Isthmus of Panama into South America. These two isolated populations evolved in different directions due to

Figure 12.21: Alfred Russel Wallace identified six major biogeographic regions: Nearctic, Neotropical, Palaearctic, Ethiopian, Oriental, and Australian Regions. Wallace explained the distributions of many animals and plants as a result of changes in geography and evolution.

differences in chance variations and habitat. Today's descendants are llamas and guanacos in South America, and camels in Asia. Asian camels continued to migrate west into Africa, giving rise to two species – the dromedary in Africa, and the Bactrian in eastern Asia.

The distribution of some older fossils shows an opposite pattern; for example, fossils of a single species of fern, *Glossopteris*, have been found in South America, Africa, India, Antarctica, and Australia (**Figure** 12.23). Putting together many such distributions and a great deal of geologic data, Alfred Wegener showed that the continents were long ago united as Gondwanaland, and have since drifted apart. His theory of **continental drift** and its modern form, **plate tectonics**, help to further explain patterns of evolutionary descent in space and time.

Island Biogeography

Island biogeography studies archipelagos (oceanic island chains) as isolated sites for evolution. Both Darwin and Wallace used examples from isolated oceanic islands, such as the Galapagos and Hawaii, in their arguments for evolution and natural selection. Until humans arrived, terrestrial mammals and amphibians were completely absent on these islands. Darwin and Wallace showed that the animals and plants which were present had blown or drifted from one of the continents, or had descended – with modifications which suited the new habitats – from one of the original colonists. Terrestrial mammals and amphibians, having no powers of dispersal across oceans (until humans came along), were understandably absent.

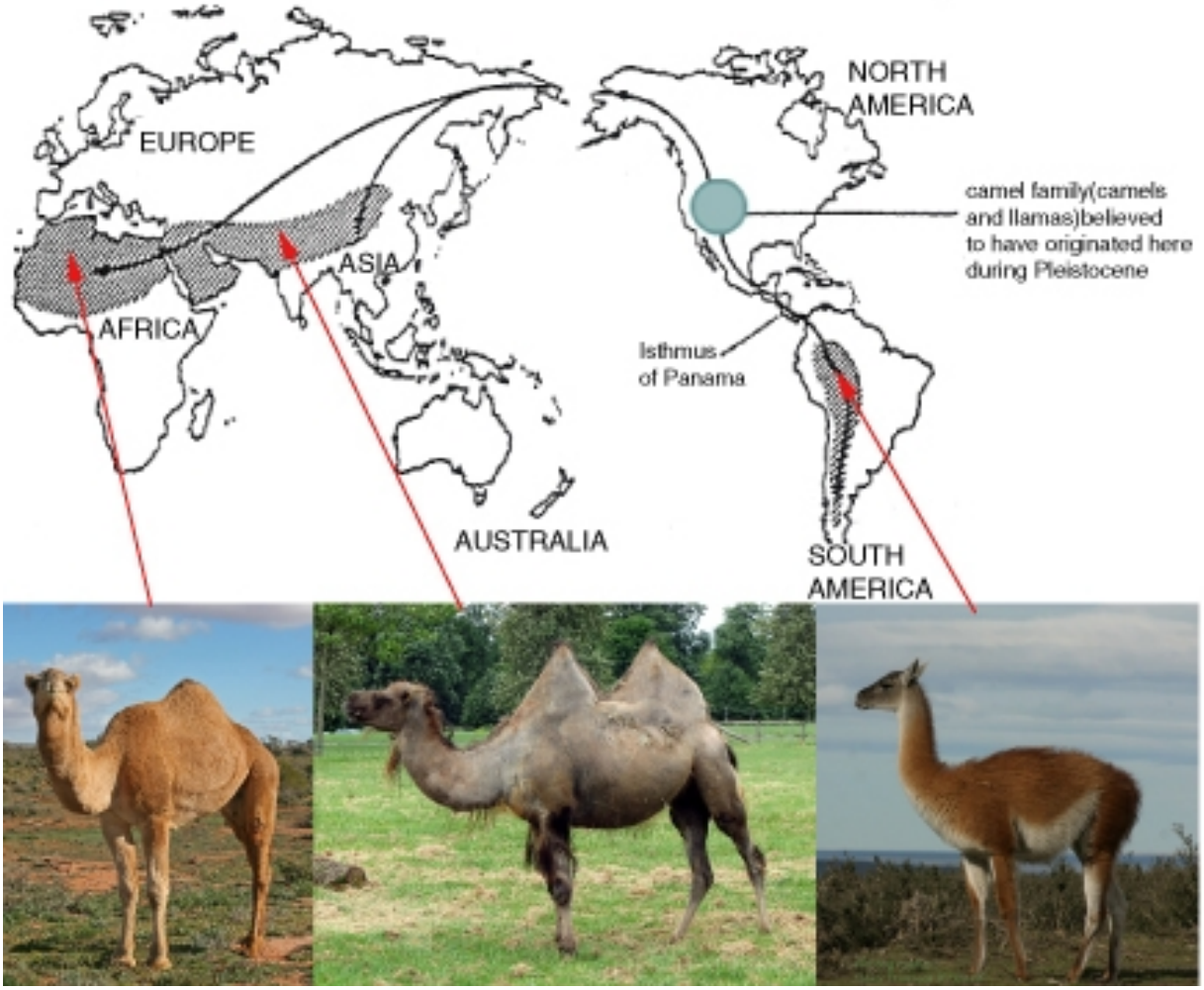

Figure 12.22: Biogeography explains the distribution of camel-like animals as a result of geographical changes and independent evolution. Today, the descendants of early camel ancestors are the dromedary in Africa, the Bactrian camel in Asia (center), and the guanaco (right) and llamas of South America.

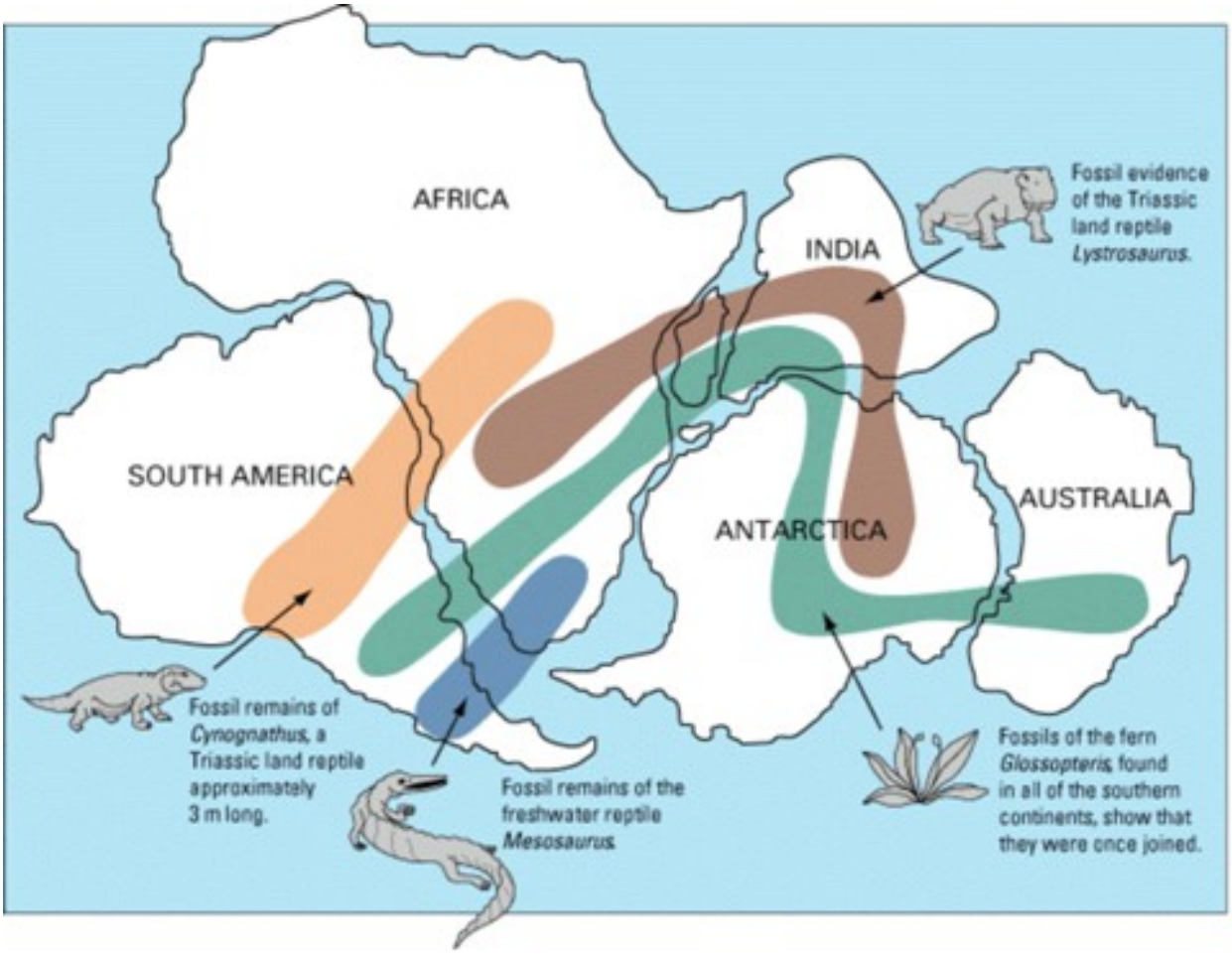

Figure 12.23: The locations of fossils such as Glossopteris on widely separated continents form contiguous patterns if the continents are joined. These patterns led to the theory of plate tectonics. Gondwanaland, a supercontinent of long ago, played an important part in evolution, natural selection and the history of life.

Darwin's Finches

Only long after returning from his voyage did Darwin, with help from ornithologist John Gould, realize that the Galapagos birds he had collected but dismissed as uninteresting blackbirds, grosbeaks, finches, and a wren, were actually all closely related descendants of a single ancestral finch which had relatives on the South American mainland. Careful analysis showed that each of the 12 new species was confined and adapted to a specific habitat on a specific island. The finches, now known as "Darwin's finches" (**Figure A** 12.24), clearly support both descent with modification and natural selection. Hawaiian honeycreepers (**Figure B** 12.24) are a more colorful but also more endangered example of the same evolutionary process of **adaptive radiation**. Bills ranging from thick and heavy (finch-like) for seed-eaters to long and curved for probing flowers illustrate the variations by which descendants of a single, original finch-like colonizer adapted to multiple ecological niches on the islands. Unfortunately, human destruction of habitat and introductions of rodents, the mongoose, and the mosquito which carries avian malaria have caused the extinction of 15 honeycreeper species, and still threaten the species which remain.

Figure 12.24: Darwin's finches (above) on the Galapagos and honeycreepers (right) on Hawaii show the adaptive radiation of single finch ancestors which first colonized the islands. Each species show descent with modification, and the variety of bill shapes show adaptation to a specific niche. Many similar examples from island biogeography support evolution and natural selection. Honeycreepers are the finch-like palila (top right), the flower-probing I'iwi (center), and another nectar feeder, the amakihi (bottom).

Scientific Evidence

Altogether, the fossil record, homologies, analogies, vestigial structures, molecular uniformity and diversity, and biogeography provide powerful scientific evidence for the descent of today's species from common ancestors. Some details of natural selection have been and are still being modified. However, the remarkable biological discoveries of the 150 years since Darwin published *The Origin of the Species* have dramatically strengthened support for his theory. Moreover, Darwin's theory continues to enlighten new discoveries. Perhaps we could paraphrase Dobzhansky: Everything in biology makes sense in the light of evolution. The only piece still missing from the evidence puzzle is direct observation of the process itself. Darwin thought that humans could never witness evolution in action because of the vast time periods required. For once, however, he was mistaken; evolution in action is the subject of the next lesson.

Lesson Summary

- Evolution is not "just a theory" as a scientific theory, it explains and unifies the entire field of biology and has a great deal of evidence supporting it.
- The evidence includes the comparisons and observations Darwin included in his *Origin,* and new knowledge from genetics and molecular biology, added since the Origin was published.

- Darwin used the fossils known in his time as evidence for his ideas, and today's record is even more convincing.
- Often, fossil species first appear in older rocks, and disappear in younger rocks, providing evidence that species change.
- Changes in climate indicated by geology correlate with changes in fossil species and their adaptations, supporting the idea of natural selection.
- The fossil record for horses shows gradual changes which correspond to changes in the environment.

- Many basic similarities in comparative anatomy support recent common ancestry.
- Similarities in structure for closely related species are homologous.
- Similarities in structure among distantly related species are analogous if they evolved independently in similar environments. They provide good evidence for natural selection.
- Examples of evidence from embryology which supports common ancestry include the tail and gill slits present in all early vertebrate embryos.
- Vestigial structures are reduced and perhaps even nonfunctional, but homologous to fully developed and functional similar structures are in a closely related species; these support the idea of natural selection.

- Cavefish without sight or pigment and humans with goose bumps illustrate the concept of vestigiality.

- The universality of DNA for genes, amino acids to build protein enzymes and the Genetic Code is strong evidence for common ancestry.
- Similarities in metabolic pathways such as DNA replication and transcription and cellular respiration are further evidence for common ancestry.
- Within these similarities are differences in the sequence of As, Ts, Cs, and Gs due to the accumulation of mutations.
- Comparison of DNA sequences supports descent with modification and can be used to clarify evolutionary relationships.
- A Cladogram is a tree-like diagram showing evolutionary relationships which can be construction from one or a number of kinds of comparison data; DNA sequence comparisons are often used.
- Darwin's Theory of Evolution is strongly supported and also helps to explain many more recent discoveries, such Mendel's work in genetics and the molecular biology of DNA and protein.

- Changes in geographic features such as land bridges explain puzzling fossil species distributions.
- Older fossil distributions suggest that the continents have joined and separated during Earth's history.
- Plate tectonics explain the distant locations of closely related species as the result of continental drifting.
- Both Darwin and Wallace proposed that oceanic island chain species often descended from a single colonizing mainland species and adapted to open niches through natural selection.
- Galapagos finches (Darwin's finches) and Hawaiian honeycreepers each fill many different ecological niches as the result of adaptive radiation from a single colonizing finch-like ancestor.

Review Questions

1. Why is it wrong to say that the Theory of Evolution is "just a theory"?
2. How did Darwin use the fossil record to support descent from common ancestors and natural selection?
3. Summarize how the fossil record for ancestors and relatives of the horse supports the relationship between evolution and changing environments.
4. Compare and contrast homologous and analogous structures as evidence for evolution.
5. Give two examples of evidence from embryology which support common ancestry.
6. Use an example to show how vestigial structures support evolution by natural selection.

7. List the molecular similarities found in all species of organisms, which support common ancestry.
8. Interpret the following cladogram in terms of evolutionary relationships and the DNA data which could have been used to construct it.

9. Relate the distribution of plants and animals to changes in geography and climate, using at least one specific example.
10. Use a specific example to illustrate the explanation given by both Darwin and Wallace for the distribution of few, closely related species across island chains.

Further Reading / Supplemental Links

- David Quammen. 1997. The Song of the Dodo: Island Biogeography in an Age of Extinctions. Scribner.
- Jonathan Weiner, The Beak of the Finch: A Story of Evolution in Our Time (Alfred A. Knopf, 1994).

- http://darwin-online.org.uk/
- http://www.ucmp.berkeley.edu/history/evolution.html
- http://www.pbs.org/wgbh/evolution/
- http://people.delphiforums.com/lordorman/light.htm
- http://ibc.hbw.com/ibc/phtml/familia.phtml?idFamilia=196
- http://www.pbs.org/wgbh/evolution/library/01/6/l_016_01.html

Vocabulary

absolute (radioisotope) dating A technique for dating fossils based on exponential decay of a radioactive isotope incorporated into the rock at the time of its formation or the fossil at the time of the organism's death.

adaptive radiation A pattern of speciation which involves the relatively rapid evolution from a single species to several species to fill a diversity of available ecological niches.

analogous traits Similar structures with identical functions shared by distantly related species; analogous traits result from natural selection in similar environments, but they evolve independently.

biogeography The study of patterns of distribution of species on continents and islands.

cladogram A tree-like diagram showing evolutionary relationships according to a given set of data, such as molecular data.

comparative anatomy The study of the similarities and differences in organisms' structures.

comparative embryology The study of the similarities during the embryological development of vertebrate animals; reveals homologies which form during development but may later disappear.

embryology A branch of comparative anatomy which studies the development of vertebrate animals before birth or hatching.

fossil The mineralized remains of an animal, plant, or other organism.

fossil record An arrangement of all known fossils according to their position in time, using rock layer and radiometric dating.

homologous structures Structures which descended (evolved) from the same structure within a common ancestor; may or may not serve the same function.

homology Similarity which has resulted from shared ancestry.

hypothesis A proposed, testable answer to a question or explanation of an observation.

island biogeography The study of archipelagos (oceanic island chains) as isolated sites for evolution.

paleontology The study of fossils to explore the history of life.

relative dating A technique for aging fossils based on comparing their positions within rock layers; fossils in lower layers are usually older than fossils in upper layers.

theory An explanation which ties together or unifies a large group of observations.

vestigial structure Structures which are reduced and perhaps even nonfunctional in one species but homologous to functional structures in a closely related species.

Points to Consider

- Which type of evidence for evolution is most convincing to you?
- Evidence confirms that evolution is a powerful theory. What other examples of theories have you encountered in your study of science? How would you compare their importance to the importance of evolution?
- In this lesson, we have used the terms hypothesis, law, and theory. How would you explain the differences between these scientific ideas?

12.3 Lesson 12.3: Evolution Continues Today - Can We Control It?

Lesson Objectives

- Recognize that the process of evolution by natural selection continues to change our world and our selves, both despite and because of our best efforts to control it.
- Understand that we have added direct observation of natural selection to the evidence for evolution.
- Evaluate the importance of artificial selection to human life.
- Discuss our use of hybridization to improve yield and adapt crops to many climates.
- Explain how cloning contradicts the principles of natural selection.
- Compare genetic engineering to traditional methods of breeding and domestication.
- Use the concept of natural selection to explain the resistance of bacteria to antibiotics and insects to pesticides.
- Explain why an individual bacterium cannot *on its own* change from sensitive to resistant towards antibiotics.
- Assess the severity of the problem of antibiotic resistance.
- Recognize that viral epidemics occur when chance viral mutations adapt the virus to new hosts.
- Describe the evidence for natural selection among Darwin's finches documented by the Grants.

Introduction

Much of the immediate success of Darwin's book was due to his careful comparison of his new idea of natural selection to the well-known breeding of animals. Darwin was especially interested in pigeons, and his observations of their many varieties inspired his own early thinking. Humans have relied on **artificial selection** ever since we first put seeds in the ground some ten thousand years ago. Today, our continuing efforts to develop crops and animals for food, work, and companions have expanded beyond breeding to include genetic engineering. Dismay about our effects on the environment is encouraging us to see ourselves

more as a part of nature than above it; perhaps we will eventually abandon Darwin's term "artificial selection" in favor of **coevolution**. Evolution by natural selection is not just an explanation of the history of life. The process of Darwin's theory clearly continues, changing our world and ourselves - both despite and because of our best efforts to control it. And we have reached beyond Darwin's wildest expectations; we now have direct observations of **natural selection** to add to the overwhelming evidence for evolution.

Artificial Selection - or Coevolution?

The range of variations induced in relatively short periods of time by animal breeders convinced Darwin that natural selection across **geologic time** could have produced the great diversity of present life. Domestication of animals has resulted in the remarkable variety of dogs (**Figure** 12.25) from wolves, as well as cattle, horses, llamas, camels, and a few evolutionary dead-ends, such as the donkey.

Figure 12.25: Selective breeding has led to dramatic differences among breeds in a relatively short time, yet dogs are still able to interbreed with wolves - the wild species from which they originated. Darwin used his observations of artificial selection, as he called it, to derive and promote his theory of evolution by natural selection.

However, artificial selection has resulted in the achievement that extends far beyond our immediate, intentional goals. Our initial cultivation of plants such as corn (**Figure** 12.26) played a role in the eventual development of human civilization.

Since Darwin's time, selective breeding and **hybridization** – mixing of separate species - has become even more sophisticated. We have further hybridized high-yield hybrids with local varieties throughout the world, intentionally adapting them to local climates and pests. Unfortunately, our widespread destruction of habitat is eroding the species and genetic diversity which provides the raw material for such efforts. Moreover, against our intent, our hybrids sometimes interbreed with natural varieties in the wild, leading to what some call **genetic pollution**. An example is a tiger, thought to be pure Bengal but actually a Bengal-Siberian hybrid, released in India to demonstrate the survival abilities of captive-raised tigers. The tiger did survive – to pollute the genetically pure Bengal population in a national park with northern-adapted Siberian genes (**Figure** 12.27).

Figure 12.26: Over time, selective breeding has modified teosinte's few fruitcases (left) into modern corn's rows of exposed kernels (right). Cultivation of crops such as corn and wheat gave early humans the freedom to develop civilizations.

Figure 12.27: The natural genes which adapted the Indian Bengal tiger (, left) and the Russian Siberian tiger (, right) to their unique habitats were mixed or "polluted" when a captive hybrid was released into a national park in India. The "escape" of non-native genes into a wild population is .

The new field of biotechnology has dramatically changed our quest to improve upon natural selection. Ironically, one new development intentionally undermines the very foundation of Darwin's theory. As the first mammal to be **cloned**, a sheep name Dolly showed breeders of animals from farms to racetracks that they could copy "ideal" individuals without the bothersome variation which accompanies sexual reproduction (**Figure** 12.28). Many people hope that future decisions about cloning will consider Darwin's lessons about the value of variation in unpredictable, changing environments.

Figure 12.28: Dolly, the first cloned mammal, is preserved for public display after six years of public life. Cloning can copy animals we believe are superior, but it denies the importance of variation to survival of species – a point made clear in Darwin's ideas about natural selection.

Another contribution of biotechnology is **genetic engineering**, the transfer of a gene from one organism to another. First, we inserted the human gene for insulin into bacteria, which – as bacteria use the same universal Genetic Code as we use – read the DNA and produced the human protein for use by diabetics. Many more cost-saving and designer medical advances have followed, including

- production of clotting factors for hemophiliacs
- vaccines for devastating diseases such as hepatitis B
- a breast cancer "designer drug," herceptin
- the potential for cheap, effective vaccines in fruits such as bananas

We have extended genetic engineering to agriculture, improving range, nutrition, resistance to disease, and other aspects of life. **Transgenic** animals - which possess genes from another species - now produce vaccines and hormones, serve in scientific research, and entertain us

as pets (**Figure** 12.29). However, as for traditional agriculture, fears surround potential cross-pollination and interbreeding with wild populations. Modified genes have been found in plants up to 21 km (13 miles) away from their source. If such transfers spread resistance to herbicides or pesticides to wild populations, they will have defeated their intended purpose.

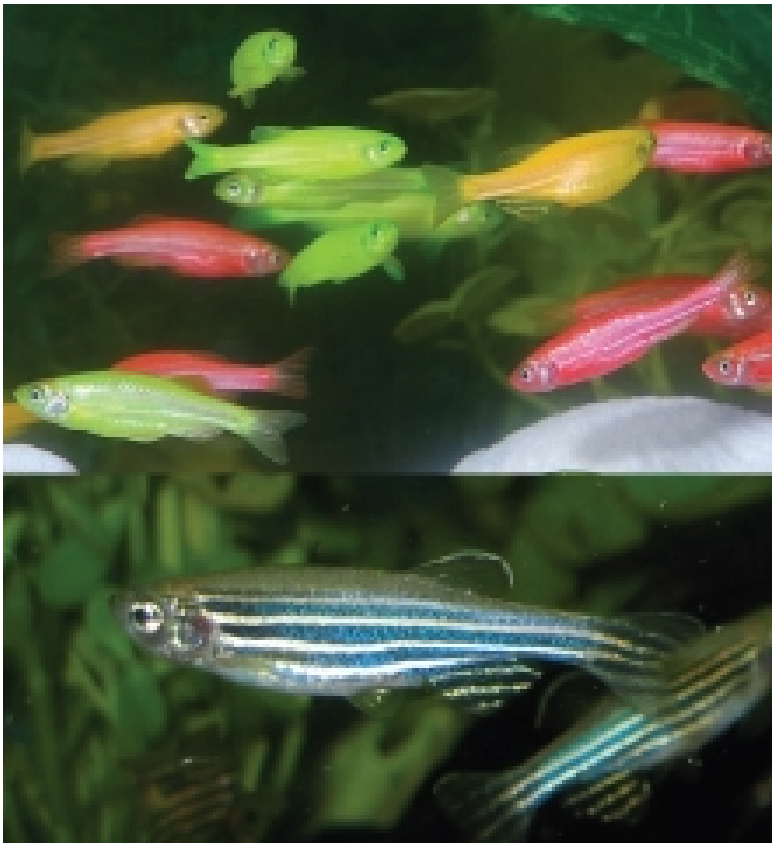

Figure 12.29: Genetic engineering has influenced our practices of medicine, research, agriculture, and animal husbandry – and recently the pet world. Zebra fish (natural species lower right) have received genes from jellyfish (green and yellow) or a coral (red) so that they glow. Originally "designed" for research, they are now bred for aquarists. Did we choose them, or did they choose us?

In his book, *The Botany of Desire*, Michael Pollan questions our feelings of superiority over our domesticated plants and animals. Discussing our domestication of the apple for its sugar, the tulip for its beauty, marijuana for its psychogenic effects, and the potato for its food value, Pollan takes the plants' view of the evolving relationships. Could it not be that, as we have selected and modified these plants, they have also selected us for our powers to ensure their survival and reproduction – and changed us in the process? Are domestication of animals, cultivation of plants, and selective breeding actually forms of coevolution? Pollan's delightful yet sobering treatise may reflect a growing realization that we humans are as much a part of nature as any other species. Yes, we can influence evolution in a number of ways.

However, we remain subject to natural selection, and every choice we make has effects on evolution – including our own. As we have already seen, and will see again in the next topic, our choices often have unintended effects.

Evolution of Resistance

In almost unprecedented actions during May 2007, United States government agencies put a US citizen on a no-fly list, urged border agents to detain him, failed to detect his re-entry into the US, and eventually ordered him into involuntary isolation, urging individuals who had flown with him on several international flights to be tested for XDR-TB. Why were such drastic measures needed? What is XDR-TB, and how did it originate? The answers show evolution in action today - in a way that all of us need to understand for our own well-being.

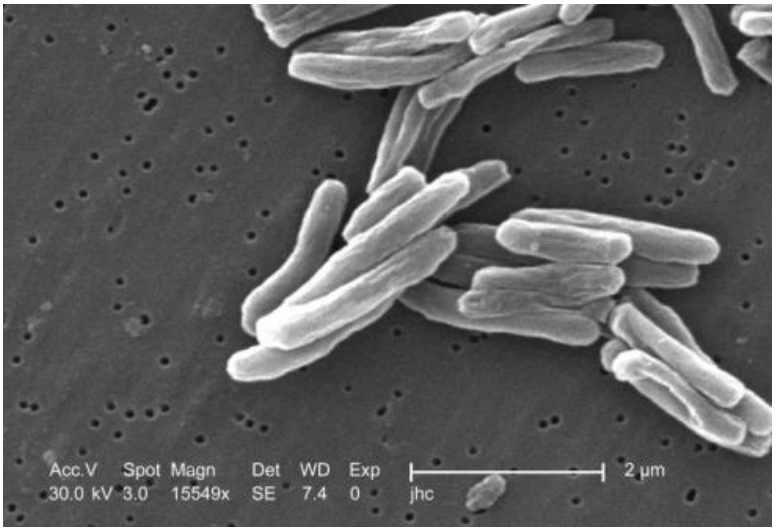

Figure 12.30: An electron microphotograph reveals the rod-shaped cells of the bacterium which causes tuberculosis (TB). We cannot, however, distinguish the antibiotic-resistant varieties by appearance; only chemical analysis can discover which patients are infected with XDR-TB. Natural selection, however, can distinguish the resistant varieties from those which are sensitive to antibiotics. Or would that be considered artificial selection, because we are (albeit inadvertently) choosing which bacteria survive?

Tuberculosis (TB) has infected and killed humans since at least 4000 BCE. Today, over one-third of the world's population has been exposed to the bacterium which causes tuberculosis (**Figure** 12.30), but 90% of those carry the microorganism without symptoms. In the past, the 10% who did develop the characteristic lung infection had a 50% chance of dying. The advent of antibiotics in the mid-20th century dramatically improved survival, although the slow-growing bacteria required treatments of 6-12 months rather than days. Just 40 years later, in the 1990s, a new strain appeared with a mortality rate comparable to lung cancer – up to 80%. MDR-TB, or multi-drug resistant TB, is not treatable by two of the most

effective anti-TB antibiotics. Then, about the year 2000, a second, more menacing strain emerged. XDR-TB, or extensively drug-resistant TB, is not treatable by either the two major drugs or the less-effective "second line" drugs now used to treat MDR-TB. Late in 2006, an epidemic of XDR-TB developed in South Africa. Currently there are no available drugs that can effectively treat this strain of TB.

Clearly these strains of TB are new, and changing rapidly. The evolution of resistance is a growing problem for many disease-causing bacteria and also for parasites, viruses, fungi, and cancer cells. The "miracle" of drug treatment which appeared to protect humans from disease may be short-lived. How does resistance happen? How can we prevent it?

First, recognize that resistance describes the bacterium (or other microorganism) – not the human. Bacteria multiply much more rapidly than humans, and therefore can evolve much more rapidly. Consider a population of bacteria infecting an individual with tuberculosis. Like all populations, individuals within that population show variation. **Mutations** add more variation. By chance, mutation may change the chemistry of one or a few bacteria so that they are not affected by a particular antibiotic. If the infected human begins to take antibiotics, they change the environment for the bacteria, killing most of them. However, the few bacteria which by chance have genes for resistance will survive this change in environment - and reproduce offspring which also carry the genes. More and more of the bacterial population will be resistant to antibiotics, because the antibiotics select for resistance. The bacteria are merely evolving in response to changes in their habitats! If the resistant bacteria are transmitted to another human "habitat," their population continues to expand, and if the new "habitat" takes different drugs, natural selection may result in multi-drug resistance (**Figure** 12.31).

How widespread is the problem? *Staphylococcus aureus* bacteria first showed resistance to penicillin just four years after the drug was put into use; today, some strains have shown resistance to nearly all antibiotics. These are now known as one of several "superbugs." The Human Immunodeficiency Virus (HIV) has become resistant to several antiviral drugs, and cancer cells within an individual often evolve resistance to chemotherapy drugs. Pesticide resistance is evolving in a similar manner; U.S. crop losses to insect pests have increased from 7% in the 1940s to more than 13% in the 1980s, despite the use of more types of pesticides in the 1980s.

What can we do about this particular instance of evolution which we have unwittingly encouraged? In general, we should reduce the use of antibiotics where possible and safe in order to lessen the selective pressure on bacteria. Here are some practices to keep in mind:

1. Don't take antibiotics for viral infections such as colds and flu; they act only on bacteria.
2. When antibiotics are appropriate, take them exactly as prescribed, and complete the entire course.
3. Never take antibiotics which are left over from an earlier illness or prescribed for someone else.
4. Consider purchasing meats and other animal products from animals not treated with

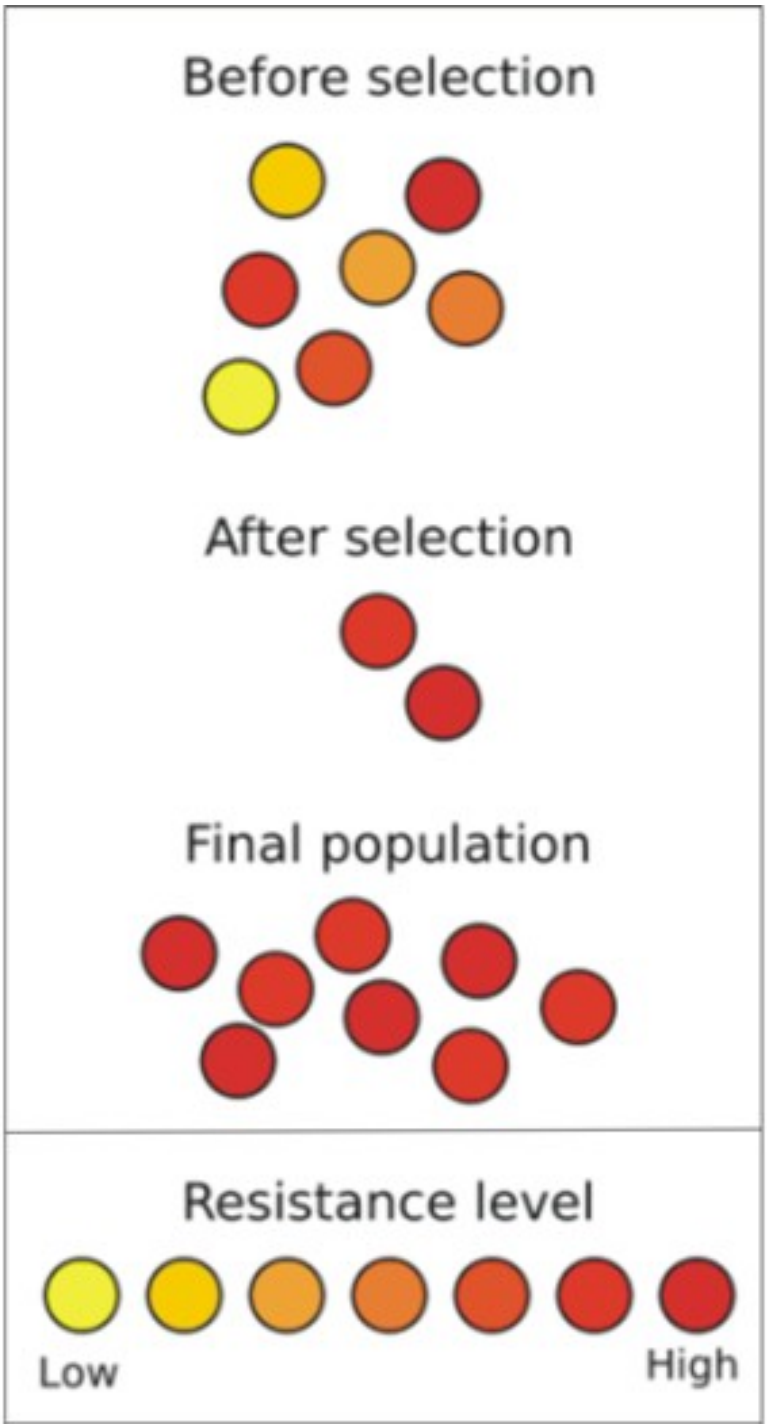

Figure 12.31: The development of resistance to antibiotics is a classic example of natural selection. , a number of heritable variations in level of resistance exist within the population (see legend at bottom). by antibiotics, only those bacteria resistant to antibiotics survive. Only these resistant bacteria reproduce, so that the contains a greater proportion of resistant bacteria.

antibiotics.
5. Consider purchasing organic produce, which is not treated with pesticides.
6. Resist the use of pesticides in your own gardens.

We have unintentionally sped up the evolution of microorganisms, but at the same time, their development of resistance has given us a window into the process which underlies all changes in life, natural selection.

Evolution Continues, and We "Catch it in the Act"

Much more passively and with a clear understanding of our lack of control, humans have watched viruses rapidly evolve through mutation to cause frightening worldwide epidemics, or **pandemics** - from the 1918 "Spanish flu" through Severe Acute Respiratory Syndrome (SARS) and West Nile virus, to the widely anticipated "avian flu" caused by a highly pathogenic viral subtype of influenza A (**Figure** 12.32), known as H5N1, and the 2009 "swine flu" caused by the H1N1 influenza virus. Figure 8 shows the increase in human infections and deaths from H5N1. Mutations have adapted it for life in birds and in humans, and for transmission from bird to bird and bird to human. If a future mutation adapts it for effective transmission from human to human, a serious epidemic could result. If, as some argue, influenza pandemics occur in cycles, we are overdue for a dramatic demonstration of evolution and natural selection.

Peppered moths (**Figure** 12.33) are mostly white with black specks – a color pattern which hid them for centuries from predatory birds as they rest against lichen covered tree trunks. However, soot from the Industrial Revolution darkened the trees and destroyed their camouflage, selecting instead for the dark mutants which occasionally appeared. Gradually the population shifted to a dark color – an instance of natural selection that was directly observed by Englishmen of the time. Subsequent improvements in air pollution control have cleaned up the environment, and the English now note a new change: the trees have lightened, and moth populations are returning to their original coloration. These direct observations of natural selection would have delighted Darwin (except perhaps for the pollution) just a few years earlier.

Much more intentionally, biologists Peter and Rosemary Grant have devoted more than 30 years to a study of two species of Darwin's finches on one of the Galapagos islands (**Figure** 12.34). Catching, weighing, and recording the seed species eaten by hundreds of these birds, they have witnessed changes in beak size which clearly correlate with changes in weather and availability of food. A severe drought and food shortage in 1977 led to a significant change. Birds whose small beaks could not crack the tough remaining seeds died, and the larger-beaked individuals who survived reproduced. The following year, offspring were larger bodied and larger-beaked, showing that natural selection led to evolution. A rainy winter in 1984-1985 reversed the trend; more soft seeds were produced, and the smaller beaked finches survived and reproduced in greater numbers than their large-beaked cousins.

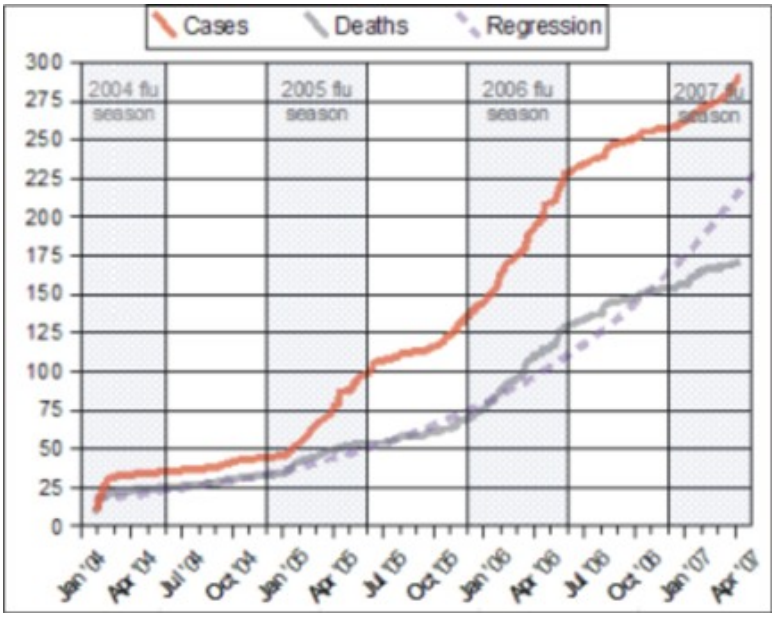

Figure 12.32: Human infections and deaths from avian flu, caused by the H5N1 subtype of influenza A virus, are clearly increasing. Mutations have adapted the virus for life in birds and humans, and for transmission from birds to birds, and from birds to humans. Some scientists think the probability is high that the virus will also evolve the means for effective transmission between humans and cause a serious pandemic.

Figure 12.33: The peppered moth population changed from mostly light (left) to mostly dark (right) as the lichen-covered trees in England's forests absorbed soot from the Industrial Revolution. Now, as pollution is being cleaned up, the moth population is returning to its former proportion of light moths. These changes illustrate what famous idea?

Figure 12.34: A large cactus ground finch crushes a seed on the island of Espanola in the Galapagos archipelago. Peter and Rosemary Grant studied two closely related species of Darwin's finches and recorded changes in beak size and body size which paralleled changes in weather. How fitting that they should demonstrate natural selection in action – something Darwin did not think possible – using one of the species he made famous!

Jonathan Winter eloquently describes the Grants' work and discoveries in his Pulitzer Prize-winning *The Beak of the Finch, A story of Evolution in our Time.* His words urging that we see evolution as ongoing for all life make a fitting conclusion to this lesson and chapter:

"For all species, including our own, the true figure of life is a perching bird, a passerine, alert and nervous in every part, ready to dart off in an instant. Life is always poised for flight. From a distance it looks still, silhouetted against the bright sky or the dark ground; but up close it is flitting this way and that, as if displaying to the world at every moment its perpetual readiness to take off in any of a thousand directions."

(*Source:* http://en.wikiquote.org/wiki/Beak_of_the_Finch)

Lesson Summary

- The process of evolution by natural selection continues to change our world and our selves, both despite and because of our best efforts to control it.
- Beyond Darwin's expectations, we have added direct observation of natural selection to the overwhelming evidence for evolution.

- Humans have designed and produced crops, work animals, and companions through artificial selection.

- Cultivation of crops gave us the freedom to develop civilization.
- Hybridization improves the yield of crop species and adapts them to various environments.
- Habitat destruction is destroying raw materials for hybridization, and "escape" of "artificial" genes is "polluting" wild species.
- Cloning has the potential to reproduce exact copies of selected individuals, but it goes against the principles which govern natural selection.
- Genetic engineering, like traditional methods of breeding and domestication, designs medicines, plants, and animals to suit our goals.
- Unlike traditional breeding, genetic engineering chooses single genes and can transfer them from one species to another completely unrelated species – making it faster, more precise, and far more powerful.
- In both GE and traditional breeding, the potential for genetic pollution remains. Pollution is probably more likely for genetic engineering because developments proceed so quickly.
- Products of genetic engineering include insulin and growth hormone, vaccines in milk and bananas, produce with longer growing season and shelf life and more nutrition.
- Michael Pollan suggests that we are coevolving with our domesticated crops, animals, and pets, rather than producing them – in other words, that our products are domesticating us as we domesticate them!

- Bacteria have developed serious levels of resistance to antibiotics because humans have introduced a new selective force into their environments (our bodies).
- An individual bacterium has its own set of genes. If these genes do not confer resistance to antibiotics, the bacterium by itself cannot develop resistance. A population can develop resistance if some of its members have, by chance, the gene for resistance.
- The evolution of antibiotic resistance has already resulted in a number of bacteria resistant to most known antibiotics; these are sometime called "superbugs."
- Actions you can take to prevent or slow the evolution of antibiotic resistance include:
- Don't take antibiotics for viral infections.
- Take prescribed antibiotics exactly as prescribed.
- Never take antibiotics which are left over or belong to someone else.
- Consider purchasing meats from animals not treated with antibiotics.
- Consider purchasing organic produce.
- Resist the use of pesticides in your own gardens.

- Viral epidemics occur when chance viral mutations adapt the virus to new hosts or new methods of transmission.
- Peppered moth populations changed color as the Industrial revolution changed the color of their habitat.
- Peter and Rosemary Grant studied two closely related species of Darwin's finches and recorded changes in beak size and body size which paralleled changes in weather.

Review Questions

1. List the ways in which we have directly observed evidence for evolution and/or natural selection.
2. Describe the importance of artificial selection to human life.
3. What is genetic pollution and why does it matter?
4. Compare cloning to natural selection.
5. Give examples of useful products of genetic engineering.
6. Explain Michael Pollan's ideas about our relationship with our domesticated crops, animals, and pets, and give your opinion about them, using examples from your own experience.
7. Use the concept of natural selection to explain the resistance of bacteria to antibiotics and insects to pesticides.
8. Explain why an individual bacterium cannot *on its own* change from sensitive to resistant to antibiotics.
9. Choose two actions you think would be most likely to control the increase in antibiotic resistance, and support your choices with examples from your own experience.
10. In what way do viral epidemics demonstrate evolution?

Further Reading / Supplemental Links

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- http://www.millerandlevine.com/km/evol/Moths/moths.html
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Vocabulary

artificial selection Animal or plant breeding; artificially choosing which individuals will reproduce according to desirable traits.

cloning The process of creating an identical copy of an organism.

coevolution A pattern in which species influence each other's evolution and therefore evolve in tandem.

genetically modified organism (GMO) An organism whose genes have been altered by genetic engineering.

genetic engineering The manipulation of an organism's genes, usually involving the insertion of a gene or genes from one organism into another.

genetic pollution The natural hybridization or mixing of genes of a wild population with a domestic or feral population.

geologic time Time on the scale of the history of Earth, which spans 4.6 billion years.

mutation A change in the nucleotide sequence of DNA or RNA.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

transgenic animal An animal which possesses genes of another species due to genetic engineering.

Points to Consider

- To what extent do you think that humans have removed themselves from natural selection?
- In what ways do you still feel subject to "natural" selective pressures?
- How effective do you think the measures to limit evolution of antibiotic resistance will be? Are you willing to support them?
- Do you think the benefits of genetic engineering outweigh the risks? Are there certain products you support, and others you oppose? Which ones, and why?

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Chapter 13

Evolution in Populations

13.1 Lesson 13.1: Genetics of Populations

Lesson Objectives

- Analyze the relationship between Darwin's work and Mendel's discoveries.
- Explain the goal of population genetics.
- Describe the relationship between genes and traits.
- Differentiate between genes and alleles.
- Connect alleles to variations in traits.
- Distinguish environmental effects on gene expression from allelic variations in genes.
- Describe the relationship between mutations and alleles.
- Explain the causes and random nature of mutation.
- Compare rates of mutation in microorganisms to those in multicellular organisms.
- Analyze the ways in which sexual reproduction increases variation.
- Relate mutation and sexual reproduction to natural selection.
- Explain why populations, but not individuals, can evolve.
- Define a population's gene pool.
- Distinguish between a population's gene pool and a gene pool for a single gene.
- Analyze the usefulness of the gene pool concept.
- Explain how to determine allele frequencies.
- Define evolution in terms of allele frequencies.
- Discuss what is meant by a population which is fixed for a certain gene.
- Show how allele frequencies measure diversity.
- Evaluate the significance of a change in allele frequency.

Introduction

If you have ever taken something apart to find out how it works, you will understand biologists' delight in exploring, since Darwin's findings, how evolution actually works. Darwin gave us the keys to unlocking this mystery by describing natural selection and common ancestry as a scientific explanation for the similarities and differences among the millions of Earth's species – living and extinct. However, his theory depended on the ideas that traits could vary, and that variations were heritable – and even Darwin was puzzled as to how this might work. Another biological giant, Gregor Mendel, was a contemporary of Darwin's, but his now-famous work with pea plant inheritance was not widely known or appreciated until after both scientists had died. During the 20^{th} century, "re-discovery" of Mendel's work stimulated extensive research in genetics, and the identification of DNA as the universal genetic material of life, brought "heritable variation" into sharp focus. A branch of the new field of Population Biology (discussed in the *Populations* Chapter) finally combined what Mendel and Darwin had begun separately - the exploration of population genetics and the evolution of populations.

Genetics of Populations

You have studied genetics, DNA, and Darwinian evolutionary theory in previous chapters. You have had the opportunity to learn far more about biology than either Darwin or Mendel could imagine. You are prepared, then, to join biologists in exploring how evolution works. You know that biologists have massive amounts of evidence that **natural selection** and evolution happen. This chapter will explore what we know about how molecules, genes, and populations change – with the ultimate goal of understanding how the "Origin of Species" produced the vast diversity of life on Earth.

Genes and Alleles

As you've learned, each cell of an organism contains all the information needed to build the entire organism in the DNA of its chromosomes (**Figure** 13.1). A **gene** is a segment of DNA which has the information to code for a protein (or RNA molecule) (**Figure** 13.2). For many genes, the protein product controls or at least contributes to a particular trait. For example, enzymes are proteins which are important in the biochemical reactions controlling many cellular processes.

For example, the gene for the enzyme *tyrosinase* controls the chemical reaction which makes melanin, a brown-black pigment which colors the skin and hair of many animals, including humans. The gene is the "recipe" for tyrosinase; tyrosinase is the protein, and the trait is coloring of the skin or fur. The rabbit in **Figure** 13.3 has brown fur because its DNA contains a gene for tyrosinase.

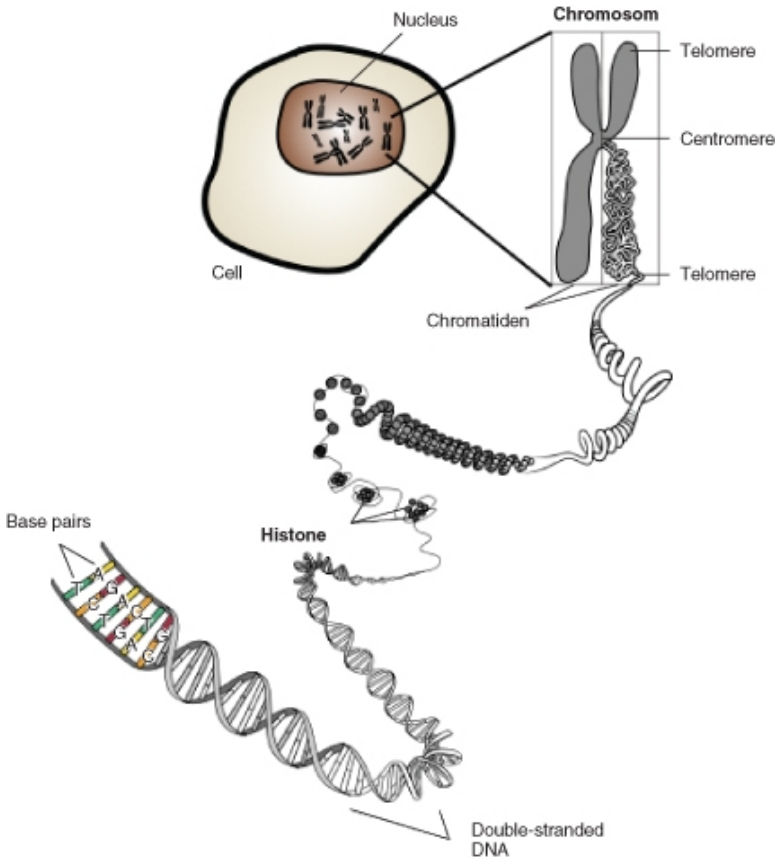

Figure 13.1: The source of variation required for natural selection is not traits or characters, as Darwin predicted, but the underlying genes, which were not discovered until Mendel's work became known. Genes are segments of DNA located at a particular place on a chromosome. The gene's sequence of bases codes for a protein - often an enzyme that catalyzes a particular chemical reaction in the cell. The chemical reaction determines or contributes to a physical trait or behavior.

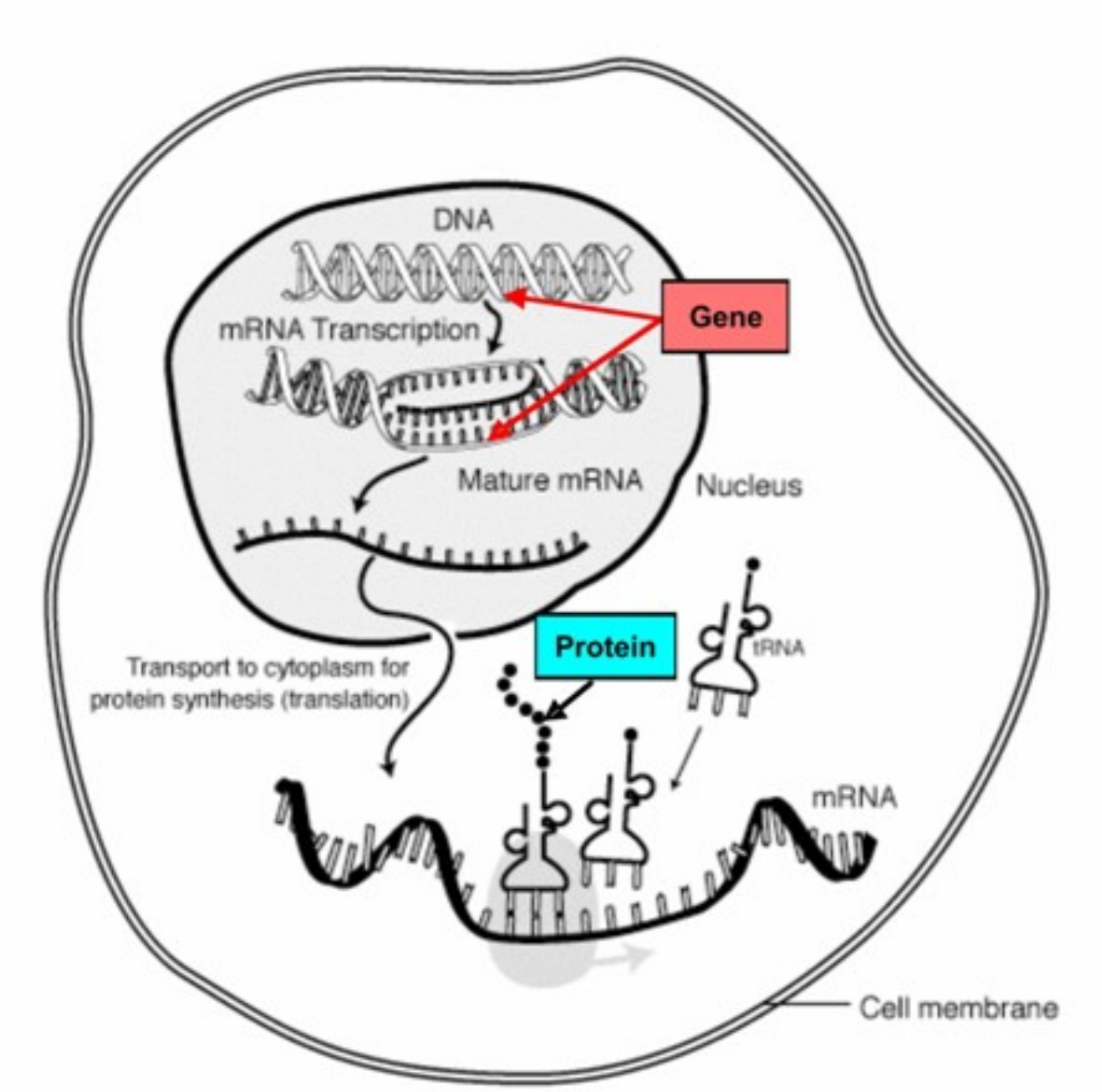

Figure 13.2: A gene is a segment of DNA which codes for a protein. Proteins, in turn, determine traits. Changes in genes (mutations) cause changes in proteins, which in turn produce variation in traits.

Figure 13.3: Most wild rabbits have brown fur because their DNA contains a gene which codes for tyrosinase – an enzyme which makes the pigment, melanin.

Genes often have different forms – slightly different nucleotide sequences – known as **alleles**. In some rabbits, an alternative form of the gene for fur color makes non-functional tyrosinase. A change in the sequence of As, Ts, Cs, and Gs changes the sequence of amino acids in the protein and alters or destroys its activity. This allele is recessive, and can cause lack of pigment – an albino rabbit (**Figure** 13.4). We will refer to the dominant gene for brown fur as *B,* and the recessive gene for albinism as *b.*

Figure 13.4: If a rabbit receives two copies of the mutant allele for tyrosinase, it will lack pigment altogether – a condition known as albinism. Although these rabbits are obviously domesticated, mutations leading to albinism do occasionally occur in wild populations.

Recall that Mendel showed that humans and rabbits have two copies of each gene, or "herita-

ble unit" – one from each of our parents. The two alleles we received make up our **genotype.** For simple Mendelian traits, our genotype determines our physical appearance, or **phenotype,** for that trait. A rabbit having two copies of the mutant, recessive gene cannot make tyrosinase – or melanin; its genotype is *bb,* and its phenotype is albino. A rabbit having either one or two copies of the gene for tyrosinase makes melanin; its genotype is either *Bb* or *BB,* and in either case, because *B* is dominant, its phenotype is brown. Brown rabbits which have *different* alleles (genotype *Bb*) are **heterozygous**, and brown rabbits with identical alleles (*BB*) are **homozygous.** Albino rabbits with identical recessive alleles (*bb*) are also homozygous.

Keep in mind that the environment can influence the **expression** of a gene – its transcription and translation to produce a protein. By preventing or promoting the expression of certain genes, the environment can cause variation in traits, but note that this influence is *not at all goal-directed* and *does not result in heritable change.* If you do not water or fertilize your garden, the plants will be short and stunted, but their small size is not a heritable change. Let's return to rabbits to see how this kind of variation happens at the level of genes and molecules.

A *third* allele for rabbit fur coloration codes for a form of tyrosinase which is temperature-sensitive. At low temperatures, the enzyme makes melanin normally. However, higher temperatures *denature* the enzyme in the same way that cooking changes egg white; at higher temperatures, the enzyme is misshapen and cannot make melanin. The rabbit in **Figure** 13.5 is homozygous for temperature-sensitive tyrosinase. The main part of its body, which has a higher temperature, is white because its tyrosinase does not work at high temperatures. The tips of the rabbit's ears, nose, and feet, however, are black, because the enzyme can work at the slightly lower temperatures of these extremities. What do you think such a rabbit would look like if it developed in the arctic? The tropics?

In conclusion, heritable variations, which Darwin knew were necessary for natural selection, are determined by the variety of alleles, or different forms of genes, which build proteins. The environment may add to the variety of phenotypes by influencing their expression, but the genes themselves remain unchanged. Only genes and their alleles can be sources of heritable variations in traits.

Sources of Variation

Genetic variation results from the diversity of alleles. How do alleles form?

You may recall that **mutations** change the sequence of nucleotides in DNA. Mutations can alter single nucleotides or entire chromosomes **Figure** 13.6, and they are the sole source of new alleles.

Even a single nucleotide substitution can cause major changes in an organism; **Figure** 13.7 shows the molecular and cellular effects of the well-known substitution mutation which causes

Figure 13.5: Environment can influence the expression of a gene. California rabbits are bred for a temperature-sensitive allele of the pigment-producing enzyme tyrosinase. Cooler extremities produce melanin, but warmer body parts do not.

sickle-cell anemia in humans.

Caused by ultraviolet or ionizing radiation, certain chemicals, or viruses, mutations occur entirely by chance; they are not in any sense goal-directed. Usually, they reduce an organism's **fitness** - its ability to survive and reproduce. However, many mutations are neutral; they have no effect on an organism's fitness. A few may actually improve fitness. Sickle-cell hemoglobin (Hemoglobin S – see **Figure** 13.7) prevents malarial infection, so in equatorial environments where malaria is prevalent, one copy of the Hemoglobin-S allele increases survival and reproduction.

New alleles arise only by chance mutations, yet without them, there would be no diversity and no evolution. Although they are rare due to repair mechanisms, mutations provide the creative potential for adaptation to environmental change.

Rates of mutation depend largely on reproductive rate, and are highest in bacteria and viruses. HIV, for example, can produce over one trillion new viruses per day, and each replication of its genome provides an opportunity for mutation. Their high mutation rates explain why viruses and bacteria so often become resistant to drug treatments.

Mutations resulting in heritable variation for multicellular organisms happen constantly, but at a lower rate. In part, this is because mutations in body cells do not affect the DNA in eggs and sperm. While this prevents many damaging mutations from dooming offspring, it also reduces diversity and the potential for adaptation to changing environments. **Sexual reproduction**, however, compensates at least in part for this loss.

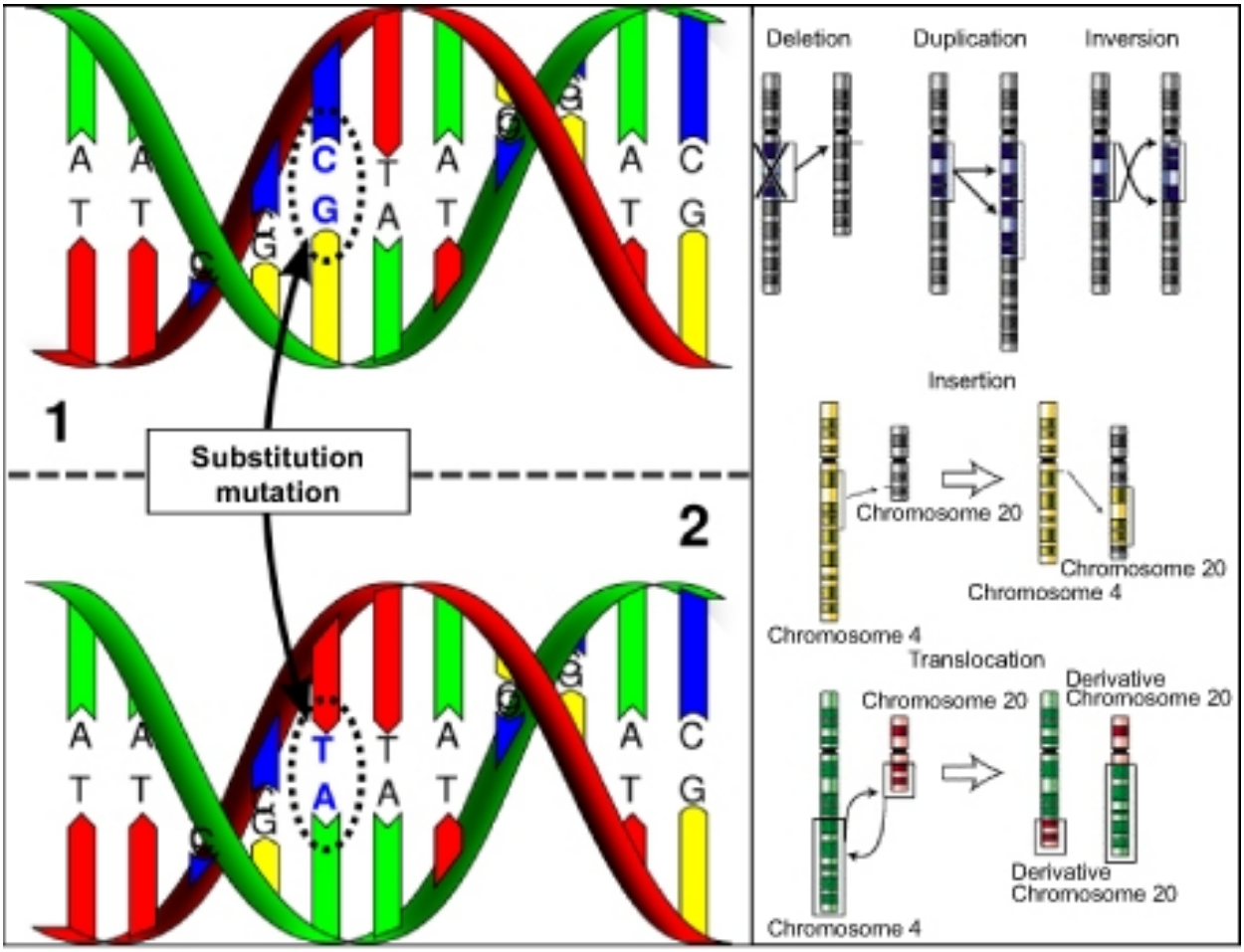

Figure 13.6: The ultimate source of genetic variation, random mutations are changes in nucleotide sequences of DNA. They may involve only a single base pair - as in (A), or many - as in chromosomal mutations (B).

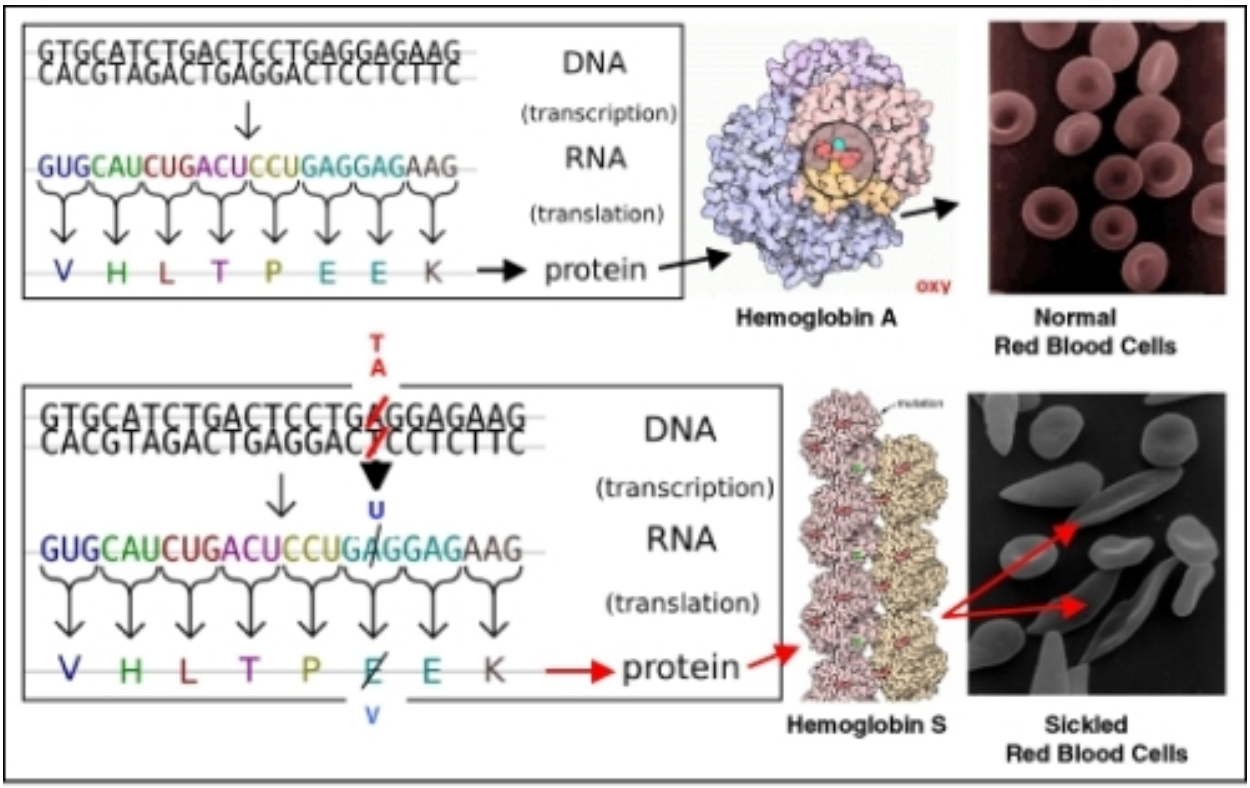

Figure 13.7: Mutations in DNA cause changes in the amino acid sequence of proteins, which in turn cause changes in traits. The disease Sickle Cell Anemia results from a single base-pair substitution in the gene for Hemoglobin. The single amino acid change dramatically alters the shape and function of the protein - and of red blood cells, which each contain 280,000 molecules of hemoglobin.

Figure 13.8: Sexual reproduction cannot produce new alleles, but it does shuffle alleles into unique combinations, adding to the raw material for natural selection.

Although sexual reproduction cannot produce new alleles, meiosis and fertilization shuffle alleles from past mutations into new combinations **Figure** 13.8. As Mendel demonstrated, genes (which he called "factors") *segregate* and *sort independently* during the formation of eggs and sperm (return to the *Mendelian Genetics* if needed), and fertilization is random. The result is that – by chance – each offspring has a unique combination of alleles – a tremendous source of variation and raw material for natural selection.

Populations and Gene Pools

Individuals do not evolve. Natural selection may affect an individual's chance to survive and reproduce, but it cannot change the individual's genes. However, a **population** – a group of organisms of a single species in a certain area – evolves when natural selection imposes differential survival on individuals within it. **Population genetics** studies populations at the level of genes and alleles in order to discover how evolution works.

If we consider all the alleles of all the genes of all the individuals within a population, we have defined the **gene pool** for that population. Gene pools contain all the genetic variation – that raw material for natural selection – within a population. The gene pool for a rabbit population, for example, includes alleles which determine coat color, ear size, whisker length, tail shape, and more (**Table** 13.1). If a population geneticist wants to focus on the variation in an individual gene, she/he may look at the gene pool of all the alleles for that gene alone.

Consider a population of 100 rabbits, including 10 albinos and 90 brown rabbits. The proportion of each phenotype is a measure of variation in this population, but it does not show the true genetic diversity. The gene pool does. Two populations of 10 white and 90

brown rabbits – with identical phenotypic diversity - could differ, because brown rabbits could be either homozygous or heterozygous.

Rabbits, like humans, are diploid. Therefore, each population's gene pool for coat color contains 200 alleles. The 10 albinos in each population contribute a total of 20 b alleles to each gene pool. However, if population #1 has 40 heterozygotes and population #2 just 20, their gene pools differ significantly.

In population #1, 50 homozygous dominant individuals contribute 100 B alleles, and the 40 heterozygotes contribute 40 more. The heterozygotes also contribute 40 albino b alleles. Thus, population #1 contains a total of 140 B alleles and 60 b alleles.

Population #2, on the other hand, has 70 homozygous dominant rabbits, which add 140 B alleles to the 20 from the heterozygotes – a total of 160 B alleles. Only 40 b alleles are present in the gene pool, so genetic diversity is lower. The use of gene pools allows population geneticists to see variation and the influence of natural selection in detail.

Table 13.1: **Table of Phenotypes and Genotypes in Two Rabbit Populations**

Phenotypes	Number of each phenotype	Genotypes	Number of each genotype	Alleles contributed to gene pool	Total gene pool
Rabbit Population #1	90	BB	50	$100B$	$140B$
					
	90	Bb	40	$40B + 40b$	
	10	bb	10–	$20b$	$60b$

Table 13.1: (continued)

Phenotypes	Number of each phenotype	Genotypes	Number of each genotype	Alleles contributed to gene pool	Total gene pool
Rabbit Population #2	90	BB	70	$140B$	$160B$
					
	90	Bb	20	$20B + 20b$	
	10	bb	10−	$20b$	$40b$

As Darwin saw, populations are the units of evolution. As Mendel showed but Darwin could not have seen, heritable units, which we now know as alleles, determine the amount of variation within a population. A measure of this variation is the population's gene pool. Once again, individuals cannot evolve, but it is the individual organism that adapts to its environment. It is the gradual accumulation of a series of adaptations - through genetic change - in a lineage from the population that is evolution.

Allele Frequencies

Our analysis of the rabbit populations (**Table** 13.1) showed that the relative numbers of various alleles are the best measure of variability in a gene pool (or a population). Population geneticists calculate the proportions, or frequencies, of each allele in order to study changes in populations. In fact, a change in **allele frequency** is the most precise measure of the process of **evolution.**

An allele's frequency is the fraction (expressed as a decimal) of a population's gene pool

made up of that particular allele. In rabbit population #1 above, the gene pool for coat color included 200 alleles, 140 of which were *B.* The frequency of allele *B* for population #1 is 140/200 = 0.7. Because frequencies must total 1.0, and the only other allele is *b,* the frequency of allele *b* is 0.3. (Alternatively, we can calculate the frequency of allele *b* by dividing the number of this allele by the total number of alleles: 60/200 is again 0.3.) In population #2, 160 of 200 alleles are *B,* so the frequency of allele *B* is 0.8, and the frequency of allele *b* is 0.2.

If all the members of a rabbit population (#3) are homozygous brown, the frequency of *B* is 1.0, the frequency of *b* is 0, and there is no diversity. Allele *B* is said to be *fixed*, and until a mutation occurs, no possibility for evolution (with respect to this particular gene) exists. A population with frequencies of 0.5 for *B* and 0.5 for *b* would have maximum diversity for this two-gene system.

Any change in those frequencies across generations would reflect **evolution** of the population – the subject of the next lesson.

Lesson Summary

- Population genetics studies populations at the level of genes and alleles in order to discover how evolution works.
- Genes - segments of DNA - determine traits by coding for enzymes that control chemical reactions.
- Many genes have several different forms known as alleles.
- Alleles are responsible for the variation in traits.
- The environment can affect the expression of some genes, but variations induced by the environment are not heritable.
- Mutations – changes in single nucleotides or entire chromosomes - are the sole source of new alleles.
- Ultraviolet or ionizing radiation, chemicals, or viruses cause mutations - in an entirely random way.
- Rates of mutation are high in rapidly reproducing viruses and bacteria, allowing them to adapt quickly to changing environments. An example is drug resistance.
- Rates of heritable mutations are lower in multicellular organisms because only germ cell mutations are passed on to offspring.
- Sexual reproduction recombines existing alleles through meiosis and random fertilization, so that each offspring is unique.
- Mutations and sexual reproduction provide the variety which is the raw material for natural selection.
- Individuals experience natural selection, but not the genetic changes of evolution.
- Populations evolve through genetic change.
- A population's gene pool includes all the alleles of all the genes of all the individuals within it.

- A gene pool for a single gene includes all the alleles of that gene present in all individuals.
- Analysis of a gene pool can reveal variation which is not visible in phenotypes.
- Changes in allele frequency measure the process of evolution.
- Allele frequency is the decimal fraction of a population's gene pool made up of that particular allele.
- A gene pool containing only one type of allele is fixed; it lacks variation and potential for evolution, at least until mutation occurs.
- For a gene with two alleles, allele frequencies of 0.5 indicate maximum variation.
- Any change in allele frequency reflects evolution of a population.

Review Questions

1. Describe the relationship between genes and traits.
2. Explain the goal of population genetics.
3. Differentiate between genes and alleles.
4. Distinguish environmental effects on gene expression from allelic variations in genes.
5. Describe the relationship between mutations, alleles, variation, natural selection, and chance.
6. Compare rates of mutation in microorganisms to those in multicellular organisms.
7. Explain why populations, but not individuals, can evolve.
8. Distinguish between a population's gene pool and a gene pool for a single gene.
9. Explain how to determine allele frequencies.
10. Evaluate phenotype, genotype, and allele frequencies as measures of variation, as raw material for evolution, and as a measure of evolution.

Further Reading / Supplemental Links

- http://library.thinkquest.org/19037/population.html
- https://www3.nationalgeographic.com/genographic/
- http://darwin.eeb.uconn.edu/simulations/simulations.html
- http://chroma.gs.washington.edu/outreach/genetics/sickle/sickle-bean.html

Vocabulary

allele An alternative form or different version of a gene.

allele frequency The fraction (usually expressed as a decimal) of a population's gene pool made up of a particular allele.

evolution A change in the frequency of an allele (or genetic makeup) in a population.

fitness The ability of an organism with a certain genotype to survive and reproduce, often measured as the proportion of that organism's genes in all of the next generation's genes.

gene A segment of DNA which codes for a protein or RNA molecule; a unit of inheritance.

gene pool Within a population, the sum of all the alleles of all the genes of all the individuals.

genotype The genetic makeup of an organism; specifically, the two alleles present.

heterozygous Describes a genotype or individual having two different alleles for a gene.

homozygous Describes a genotype or individual having two copies of the same allele for a gene.

mutation A change in the nucleotide sequence of DNA or RNA.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

phenotype The physical appearance of an organism determined by a particular genotype (and sometimes also by the environment).

population A group of organisms of a single species living within a certain area.

population genetics The study of the evolution of populations at the level of genes and alleles.

sexual reproduction Two-parent gamete based reproduction, involving meiosis and fertilization.

Points to Consider

- Imagine how Darwin felt, knowing that traits were passed on to offspring and that heritable variations "somehow" appeared. What key discoveries now explain these facts?
- As we noted in the last chapter, Theodosius Dobzhansky is famous for his statement, "Nothing in biology makes sense except in the light of evolution." Do you agree that people cannot understand biology without understanding evolution?
- How does evolutionary theory "make sense of" your similarities to your parents and siblings? Your differences from them? Similarities among all humans? Differences among us?

13.2 Lesson 13.2: Genetic Change in Populations

Lesson Objectives

- Compare and relate macroevolution to microevolution.
- Define microevolution in terms of allele frequencies.
- Define genetic equilibrium for a population.
- List the five conditions for genetic equilibrium according to the Hardy-Weinberg model.
- State and explain the generalized equation for Hardy-Weinberg equilibrium.
- Explain how to use the Hardy-Weinberg equation to solve for allele or genotype frequencies.
- Discuss the reasons why the 5 conditions for Hardy-Weinberg equilibrium are rarely met.
- Explain how mutation disrupts genetic equilibrium.
- Predict the possible effects of mutation, and analyze the probability of each type of effect.
- Contrast mutation in microorganisms to mutation in multicellular organisms.
- Define gene flow.
- Describe two possible effects of gene flow on the genetics of a population.
- Define genetic drift.
- Describe three possible effects of genetic drift on populations and/or specific alleles.
- Explain and give an example of the bottleneck effect.
- Clarify and give an example of the concept of "founder effect."
- Compare and contrast genetic drift and natural selection as causes of evolution.
- Discuss natural selection and evolution in terms of phenotypes and allele frequencies.
- Explain the distribution of phenotypes for a trait whose genetic basis is polygenic.
- Using a normal distribution of phenotypic variation, interpret directional, disruptive, and stabilizing patterns of selection.
- Define fitness as it relates to natural selection.
- Describe how natural selection can sometimes lead to the persistence of harmful or even lethal allele.
- Analyze the logic of kin selection.

Introduction

- How many people in the United States carry the recessive allele for the lethal genetic disease, cystic fibrosis?
- Why must we treat AIDS patients with multi-drug "cocktails?"
- Why do we consider Northern Elephant seals endangered, even though their population has risen to 100,000 individuals?
- Why don't South African Cheetahs reject skin grafts from unrelated individuals?
- What were the probable effects on human evolution of the six years of "volcanic winter"

caused by the "megacollosal" eruption of Mt. Toba 70,000 years ago?
- Why do humans vary in skin color?
- Why doesn't natural selection eliminate certain lethal genes?

This lesson will introduce you to our current understanding of the causes of evolution and show you how scientists use this understanding to solve problems and answer puzzling questions like those above.

Microevolution

In an earlier chapter, we defined **microevolution** as evolution within a species or population, and **macroevolution** as evolution at or above the level of species. The differences between the two are time and scale. Microevolution can refer to changes as small as a shift in allele frequencies for a single gene from one generation to the next. In contrast, macroevolution describes changes in species over geologic time. Many biologists consider evolution to be a single process; they regard macroevolution as the cumulative effects of microevolution. The *History of Life* chapter discussed patterns and processes of macroevolution; this lesson will focus on genetic changes within populations and species. At this level, we can see how evolution really works – a view that Darwin never had.

A change in allele frequencies within a population from one generation to the next – even if it involves only a single gene - is evolution. Biologists refer to this change in the gene pool as microevolution because it is evolution on the smallest scale. For our rabbit population from the previous lesson, a generation-to-generation increase in the frequency of the albino allele, *b,* from 0.3 to 0.4 (and the corresponding decrease in the frequency of allele *B* from 0.7 to 0.6) would be microevolution. The changes in Galapagos finch beak size, documented by Peter and Rosemary Grant, and the color changes of peppered moths will undoubtedly show corresponding changes in allele frequencies once we identify the responsible genes and alleles. Resistance to antibiotics in bacteria and the appearance of new strains of influenza viruses and HIV **Figure** 13.9 also involve changes in allele frequencies. Each of these is an example of microevolution.

What forces cause changes in allele frequencies? What mechanisms determine how microevolution happens? Before we tackle these questions, we will examine a population at equilibrium – a population which is *not* evolving.

Populations at Equilibrium: The Hardy-Weinberg Model

Like Darwin and Wallace, who independently developed similar ideas about evolution and natural selection, mathematician Godfrey Hardy and physician Wilhelm Weinberg independently developed a model of populations at equilibrium. The **Hardy-Weinberg model** (sometimes called a law) states that a population will remain at genetic equilibrium - with

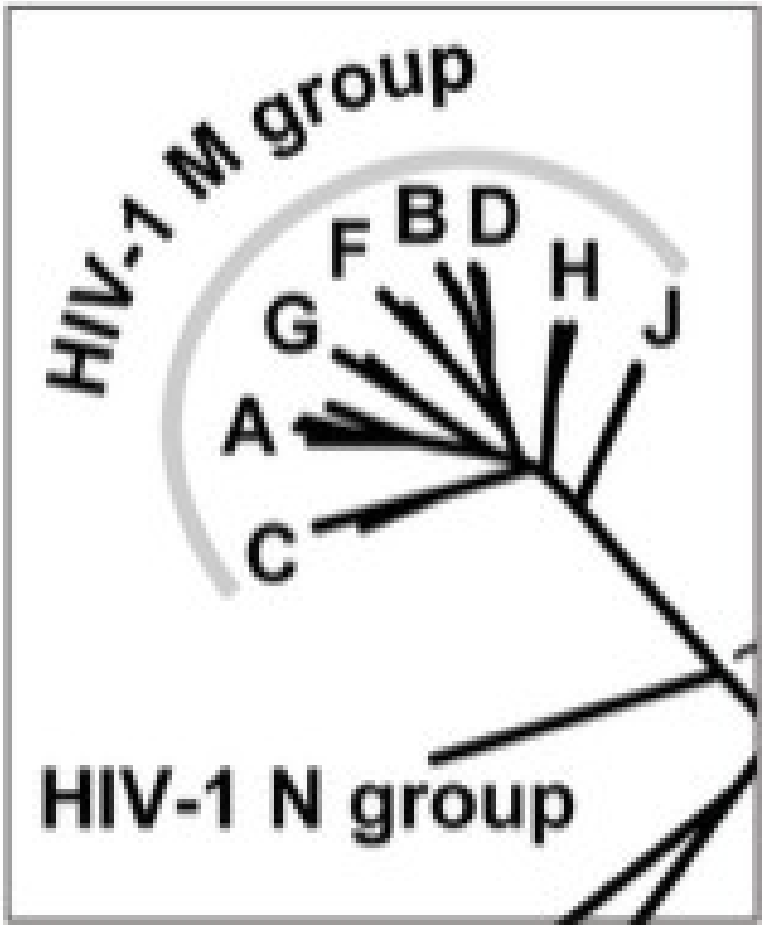

Figure 13.9: This portion of the evolutionary tree for Human Immunodeficiency Virus (HIV) shows 8 or more strains of the HIV-1 M (Main) group, and a single strain of the HIV-1 N (Not Main/Not Outlier) group. The complete tree includes strains of SIV (Simian Immunodeficiency Virus). Each strain represents a change in allele frequencies.

constant allele and genotype frequencies and no evolution - as long as five conditions are met:

1. No mutation
2. No migration
3. Very large population size
4. Random mating
5. No natural selection

We will consider the above in more detail in later sections of the lesson, because deviations from these conditions are the causes of evolutionary change. For now, let's look more closely at the Hardy-Weinberg's equilibrium model. We'll use another hypothetical rabbit population to make the model concrete: 9 albino rabbits and 91 brown rabbits (49 homozygous and 42 heterozygous). The gene pool contains 140 B alleles and 60 b alleles – gene frequencies of 0.7 and 0.3, respectively. **Figure** 13.10 summarizes the data for this parent population.

Phenotypes			
Genotypes	BB	Bb	bb
Number of Individuals (total = 100)	49	42	9
Genotype Frequencies	49/100 = 0.49	42/100 = 0.42	9/100 = 0.09
Alleles contributed to Gene Pool (total = 200)	98 *B*	42 *B* 42 b	18 *b*
Allele Frequencies	for allele *B*, (98+42)/ 200 = 0.7		For allele *b*, (42+18)/200 = 0.3

Figure 13.10: The coat color gene pool for a hypothetical rabbit population includes two alleles. Genotype and allele frequencies are calculated, given the number of individuals having each of the three possible genotypes.

If we assume that alleles sort independently and segregate randomly as sperm and eggs form, and that mating and fertilization are also random, the probability that an offspring will receive a particular allele from the gene pool is identical to the frequency of that allele in the population. A Punnett Square (**Figure** 13.11) using these frequencies predicts the probability of each genotype (and phenotype) in the next generation:

Probability of Alleles in Gametes: Sperm and Eggs	0.7 B	0.3 b
0.7 B	BB 0.7 X 0.7 = 0.49	Bb 0.7 X 0.3 = 0.21
0.3 b	Bb 0.7 X 0.3= 0.21	bb 0.3 X 0.3 = 0.09

A	BB	Bb	bb
Genotype Frequencies In Next Generation	0.49	0.21+0.21=0.42	0.09
B	B	b	
Allele Frequencies In Next Generation	0.49 + 0.49 + 0.42 = 1.40/2 = 0.7	0.42 + 0.09 + 0.09 = 0.60/2 = 0.3	

Figure 13.11: A Punnett Square predicts the probability of each genotype and phenotype for the offspring of the population described in . A summarizes the frequencies of each genotype among offspring, and B calculates allele frequencies for the next generation. Comparing these to the parent generation shows that the gene pool remains constant. The population is stable – at a Hardy-Weinberg equilibrium.

If we calculate the frequency of genotypes among the offspring predicted by the Punnett square, they are identical to the genotype frequencies of the parents. Allele frequency remains constant as well. The population is stable – at a Hardy-Weinberg **genetic equilibrium.**

A useful equation generalizes the calculations we've just completed. Variables include $\boldsymbol{p}$ = the frequency of one allele (we'll use allele $\boldsymbol{B}$ here) and $\boldsymbol{q}$ = the frequency of the second allele ($\boldsymbol{b}$, in this example). We will use only two alleles, but similar, valid equations can be written for more alleles.

Recall that the allele frequency equals the probability of any particular gamete receiving that allele. Therefore, when egg and sperm combine, the probability of any genotype (as in the Punnett square above) is the product of the probabilities of the alleles in that genotype. So:

Probability of genotype $\boldsymbol{BB} = \boldsymbol{p}$ X $\boldsymbol{p} = \mathbf{p}^2$ and

Probability of genotype $\boldsymbol{Bb}$= ($\boldsymbol{p}$ X $\boldsymbol{q}$) + ($\boldsymbol{q}$ X $\boldsymbol{p}$) = $\mathbf{2\ pq}$ and

Probability of genotype $\boldsymbol{bb} = \boldsymbol{q}$ X $\boldsymbol{q} = \mathbf{q}^2$

We have included all possible genotypes, so the probabilities must add to 1.0. Our equation becomes:

Table 13.2:

p^2	+	2 pq	+	q^2	=	1
frequency of genotype BB		frequency of genotype Bb		frequency of genotype bb		

This is the Hardy-Weinberg equation, which describes the relationship between allele frequencies and genotype frequencies for a population at equilibrium.

The equation can be used to determine genotype frequencies if allele frequencies are known, or allele frequencies if genotype frequencies are known. Let's use a common human genetic disease as an example. Cystic fibrosis (CF) is caused by a recessive allele ($\boldsymbol{f}$) which makes a non-functional chloride ion channel, leading to excessive mucus in the lungs, inadequate enzyme secretion by the pancreas, and early death (**Figure** 13.12).

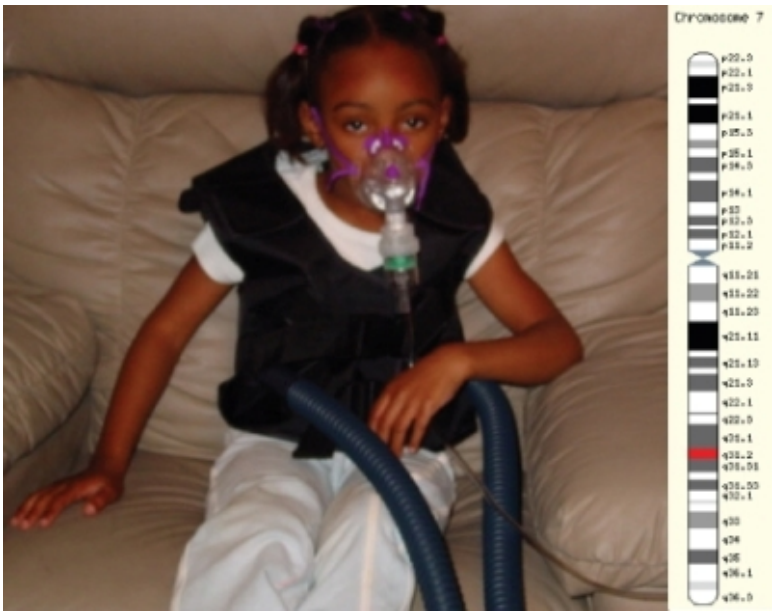

Figure 13.12: Cystic fibrosis is an inherited disease of the lungs and pancreas. A recessive allele of a gene for a chloride ion channel – located on chromosome 7 (the gene locus is colored red, right) causes the disease. Treatment includes ventilator and antibiotic therapy (above).

Knowing that 1 of every 3,900 children in the United States is born with CF, we can use the Hardy-Weinberg equation to ask what proportion of the population unknowingly carries the allele for cystic fibrosis. An individual who has CF must have the genotype $\boldsymbol{ff}$, because the allele is recessive. Using the value for the frequency of the homozygous recessive genotype, we can calculate q, the frequency of the recessive allele,$\boldsymbol{f}$:

1/3900 = 0.0002564 = frequency of ***ff*** genotypes = $\boldsymbol{q^2}$

To find $\boldsymbol{q}$, the frequency of allele ***f***, we must take the square root of the frequency of ***ff*** genotypes:

$\boldsymbol{q}$ = $\sqrt{0.0002564}$ = 0.016 = frequency of the ***f*** allele

Because $\boldsymbol{p + q = 1}$ (the sum of the frequency of allele ***f*** and the frequency of allele ***F*** must equal 1.0),

$\boldsymbol{p = 1 - q}$ = 1.0 – 0.0160 = 0.9840 = frequency of the ***F*** allele

According to the Hardy-Weinberg equation, for a population at equilibrium the frequency of carrier genotypes, ***Ff***, is **2pq** = 2 X 0.016 X 0.984 = **0.0315**.

In other words, if the population is indeed at equilibrium for this gene, just over 3% of the population carries the recessive allele for cystic fibrosis.

Of course, this calculation holds only true if the US population meets the five conditions we listed at the beginning of this section. In nature, populations seldom satisfy all five criteria. Let's consider how well each condition describes the US population for the cystic fibrosis gene:

Very Large Population Size

Although the equation ideally describes an infinitely large population – never found in nature, of course – the US population is probably large enough that this condition alone does not significantly disrupt equilibrium.

No Mutation

Mutations happen constantly, if at a low rate, so "no mutation" is a second unrealistic condition. However, mutations affecting any one particular gene are rare, so their effect on an otherwise large, stable population is small.

No Migration

This condition assumes no net additions or losses of either allele to the gene pool through immigration or emigration. For the US population, immigration is probably more significant than emigration. **Gene flow,** in essence is the flow of alleles into or out of a population, may be the most significant problem for this particular gene, because the frequency of the allele for cystic fibrosis varies greatly according to ancestry. Although 1 in 25 Europeans carry the ***f*** allele, the frequency is just 1 in 46 among Hispanics, 1 in 60 among Africans, and 1 in 90 among Asians. Therefore, disproportionate immigration by certain groups changes allele frequencies, destabilizing the Hardy-Weinberg equilibrium.

Random Mating

Here is another assumption which is probably not realistic. Marriage between individuals of similar ancestry and culture is still more common than intermarriage, although both occur.

If marriages are not random, Hardy-Weinberg equilibrium does not apply.

No Natural Selection

The final condition is that all genotypes must have an equal chance to survive and reproduce. Victims of cystic fibrosis (genotype ***ff***) have shorter lifespans, which inevitably reduce reproduction compared to individuals without the disease (genotypes ***FF*** and ***Ff***). Although medical care is improving, differential survival and reproduction among genotypes means the gene pool is not at equilibrium.

With respect to the cystic fibrosis gene, the U.S. population fails to meet at least three of the criteria for equilibrium. Therefore, the actual frequencies of alleles and genotypes probably deviate somewhat from those we calculated.

In nature, very few populations meet the Hardy-Weinberg requirements for equilibrium. If we look at this fact from a different angle, we see that any of these conditions can destabilize equilibrium, causing a change in allele frequencies. In other words, these five conditions are five major causes of microevolution. The remaining sections of this lesson will explore each cause in detail.

Causes of Microevolution: Mutation and Gene Flow

As discussed in the last lesson, mutation – a random, accidental change in the sequence of nucleotides in DNA – is the original source of genetic variation. Only mutation can create new alleles – new raw material for natural selection. UV or ionizing radiation, chemicals, and viruses constantly generate mutations in a gene pool, destabilizing genetic equilibrium and creating the potential for adaptation to changing environments. However, both rates of mutation and their effects on the fitness of the organism vary.

In multicellular organisms, most mutations occur in body cells and do not affect eggs and sperm; these are lost when the individual dies and usually do not affect evolution. Only mutations in gamete-producing cells can become part of the gene pool. The rate at which mutations enter the gene pool is low, due to DNA "proofreading" and repair enzymes - and the extensive amount of "junk" DNA which does not code for protein. Mutations which do change nucleotide sequences in functional genes may also have no effect, because the Genetic Code is redundant (multiple similar codons for a single amino acid), or very little effect, if the amino acid is not located in a critical part of the protein.

Occasionally, however, a single nucleotide substitution can have a major effect on a protein – as we saw with sickle-cell anemia in the last lesson. Usually, the effect of a mutation on a protein is harmful; rarely is it helpful. In sickle-cell anemia, it is both – in certain environments. Sickled cells carry oxygen much less efficiently, but prevent malaria infections. Overall, the chance that a single mutation will increase the fitness of a multicellular organism is extremely low. If the environment changes, however, the adaptive value of a new allele may change as well. Over time, mutations accumulate, providing the variation needed for

natural selection.

For the small genomes of viruses and bacteria, mutations affect genes directly and generation times are short, so rates of mutation are much higher. For an HIV population in one AIDS patient, rates of viral mutation and replication are so high that in a single day, every site in the HIV genome may have experienced mutation (**Figure** 13.13). This rapid generation of new alleles challenges our best efforts at drug treatment, and explains the evolution of drug antibiotic resistance. Because of the abundance of random, spontaneous mutations, HIV generates a large amount of raw material for natural selection, and readily evolves resistance to new "environments" created by single drugs (**Figure** 13.14). Drug "cocktails," which contain multiple anti-viral chemicals, are our effort to change the "environment" and keep up with mutation in the human-HIV evolutionary race. For microorganisms, mutation is a strong force for evolution.

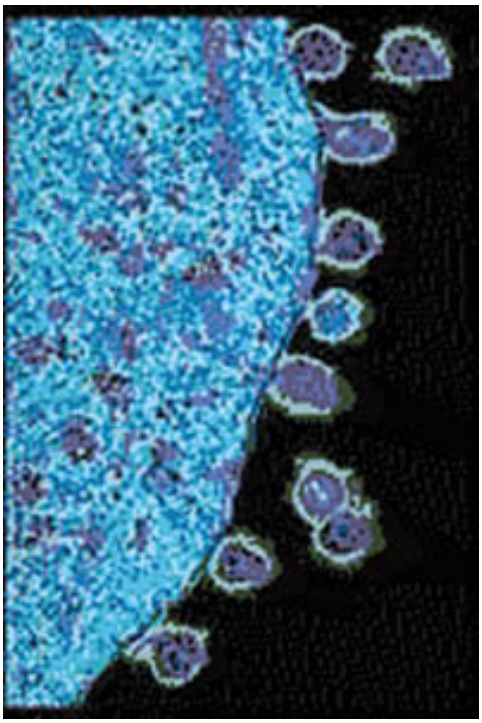

Figure 13.13: HIV daughter particles are shed from an infected human T-cell host. HIV replication and mutation rates are so high that during a single day, the HIV population in one AIDS patient generates mutations at every site in the HIV genome. New alleles provide the potential for extremely rapid evolution, including the development of resistance to drugs.

For all organisms, mutations are the ultimate source of genetic variation. For a population, however, the immigration or emigration of individuals or gametes may also add to or subtract from a gene pool – a process known as **gene flow**. For example, wind or animals can carry pollen or seeds from one plant population to another. In baboon troops or wolf packs (**Figure** 13.15), juvenile males may leave the group to find mates and establish separate populations.

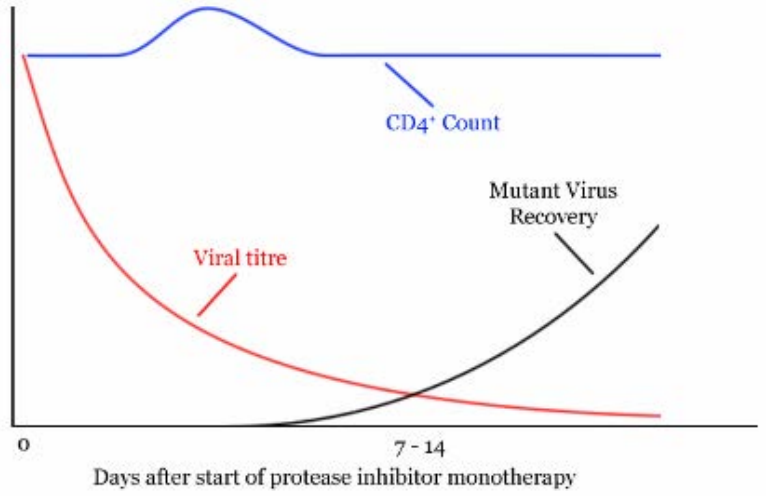

Figure 13.14: Extremely high HIV mutation rates provide many new alleles – raw material for natural selection – in AIDS patients. This variation allows at least some mutant viruses to survive and reproduce in the changing "environments" of new drug therapies. The graph shows the effects of one type of drug: an initial decrease in the HIV population and a temporary rise in the number of human host (CD4) cells. Before long, however, mutants have alleles conferring drug resistance appear and begin to reproduce, and the population recovers. This change in allele frequencies is microevolution, caused by mutation and natural selection.

Human history includes countless migrations; gene flow continues to mix gene pools and cause microevolutionary change.

Figure 13.15: Dominant alpha wolves lead their pack in Yellowstone National Park. The lowest ranking omega individual, in the rear, may eventually leave the pack to find a mate and establish his own territory and pack. He would carry some of the genes from his pack to the new one – a form of gene flow which seems built in to wolves' social organization.

Gene flow can bring into a population new alleles which occurred by chance and were successful in other populations. In this way, it can accelerate microevolution. However, if exchange between populations is frequent, it reduces differences between populations, in effect increasing population size. In this case, gene flow tends to maintain separate populations as one species, reducing speciation, if not microevolution.

Mutation, together with recombination of existing alleles by sexual reproduction (see lesson 13.1) provides the diversity which is the raw material for natural selection and evolution. Gene flow can accelerate the spread of alleles or reduce the differences between populations. Both can contribute significantly to microevolution. However, many biologists consider the major causes of microevolutionary change to be genetic drift and natural selection.

Causes of Microevolution: Population Size and Genetic Drift

Recall that the third requirement for Hardy-Weinberg equilibrium is a very large population size. This is because chance variations in allele frequencies are minimal in large populations. In small populations, random variations in allele frequencies can significantly influence the "survival" of any allele, regardless of its adaptive value. Random changes in allele frequencies in small populations are known as **genetic drift**. Many biologists think that genetic drift is a major cause of microevolution.

You see the effects of chance when you flip a coin. If you flipped a penny 4 times, you would not be too surprised if it came up heads 4 times and tails not at all. If you tossed it 100 times, you would be very surprised if the results were 100 heads and no tails. The larger the "population" of coin tosses, the lower the effects of chance, and the closer the results should match the expected 50-50 ratio. The same is true for populations. If we imagine a

rabbit population with a very small gene pool of just 2 ***B*** alleles and 2 ***b*** alleles, it is not difficult to understand that occasionally, chance alone would result in no albino offspring (only genotypes ***BB*** or ***Bb***) – or even no brown offspring (only genotype ***bb***). However, a gene pool of 100 ***B*** alleles and 100 ***b*** alleles would be very unlikely to produce a generation of offspring entirely lacking one allele or the other, despite having identical initial allele frequencies of 0.5.

Because chance governs meiosis and fertilization, random variations can influence allele frequencies, especially for small populations. Note that these chance variations can increase the frequency of alleles which have no adaptive advantages or disadvantages – or decrease the frequency of alleles which do have adaptive value. Genetic drift can result in extinction of an allele or an entire population – or rapid evolution (**Figure** 13.16). Two sets of circumstances can create small populations for which genetic drift can have major consequences: the **bottleneck effect** and the **founder effect.**

The Bottleneck Effect

Natural catastrophes such as earthquakes, floods, fires, or droughts can drastically reduce population size – usually without respect to allele frequencies. As a result of the disaster, some alleles may be lost entirely, and others may be present in frequencies which differ from those of the original population. The smaller population is then subject to genetic drift, which may further reduce diversity within the population. The loss of diversity resulting from a drastic reduction in population size and subsequent genetic drift is the **bottleneck effect** (**Figure** 13.17). Much of our concern for endangered species derives from our understanding of the way in which small population size can reduce diversity by increasing genetic drift. We will look at two examples of the bottleneck effect – one caused by humans, and the other probably experienced by our human ancestors.

During the 19th century, overhunting reduced the worldwide population of Northern Elephant Seals (**Figure** 13.18) to fewer than 100 individuals. Because an alpha bull typically mates with a "harem" of 30-100 females, it is possible that just a single male fathered all the seals which exist today! After legal protection, their numbers have rebounded to 100,000. However, the effects of the past bottleneck - significant loss of genetic variability – remain. Reduced genetic diversity means that today's seals are more susceptible to disease and weather. Effects of genetic drift on the gene pool may have contributed to the loss of 80% of pups during the El Nino year of 1997-98.

Although the exact cause is unknown, a bottleneck for South African Cheetahs (**Figure** 13.19) during the last ice age about 10,000 years ago has apparently led to extremely low genetic variability. Genetic variation among cheetahs has been compared to that of highly inbred varieties of laboratory mice; skin grafts between unrelated individuals are not rejected. These animals also suffer from low sperm counts. Like many endangered species, cheetahs are threatened not only by habitat loss, but also by reduced genetic diversity, which reduces

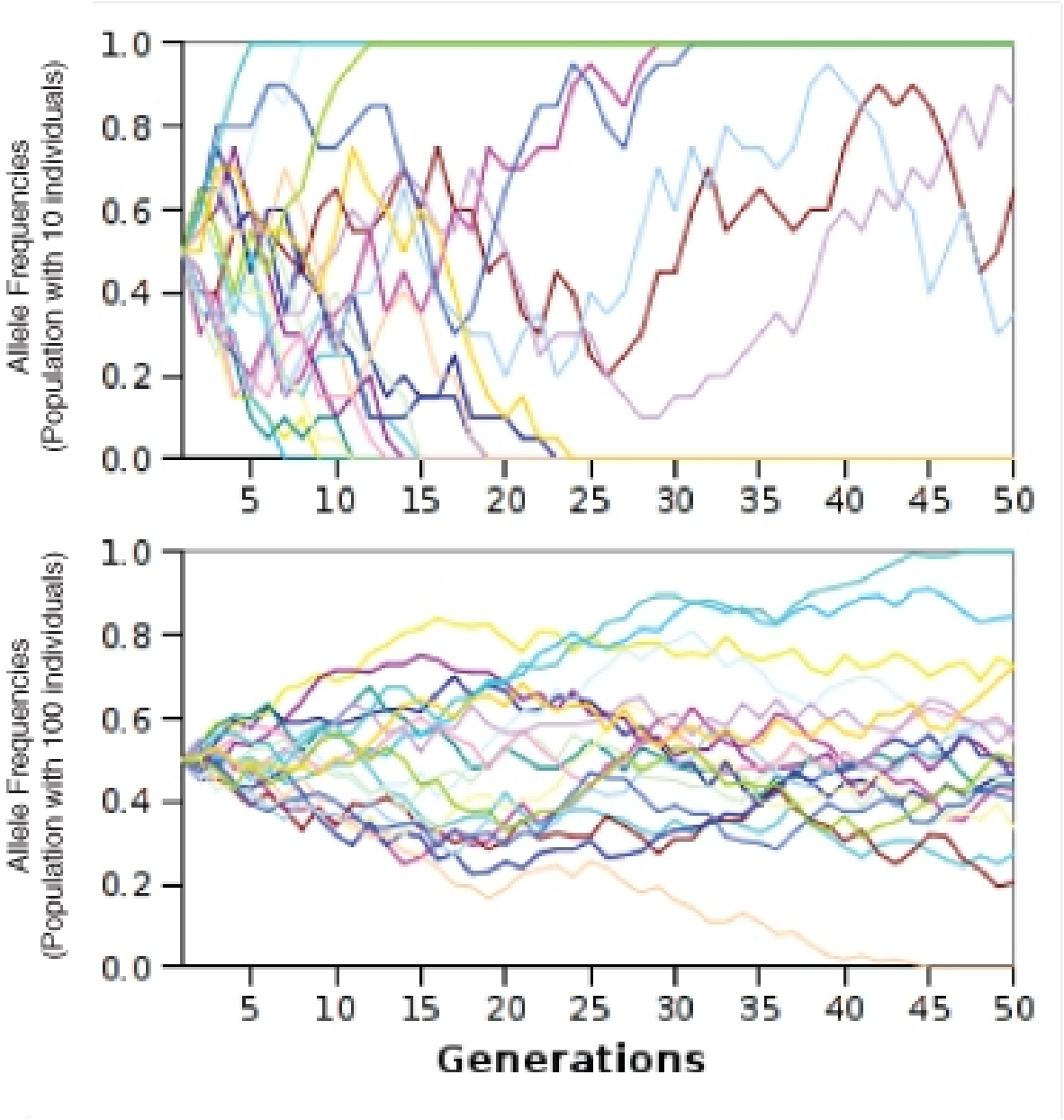

Figure 13.16: Computer models show that the effect of small population size on allele frequencies is a significant increase in variation due to chance. Each line depicts a different allele. In the small population (above), most of 20 alleles, beginning at frequencies of 0.5, become either "fixed" (frequency = 1.0) or extinct (frequency = 0) within 5 – 25 generations. In the larger population (below), only one pair of alleles shows fixation/extinction – and that occurs only after 45 generations. Note that these variations are independent of natural selection; they do not necessary fit the organism to its environment.

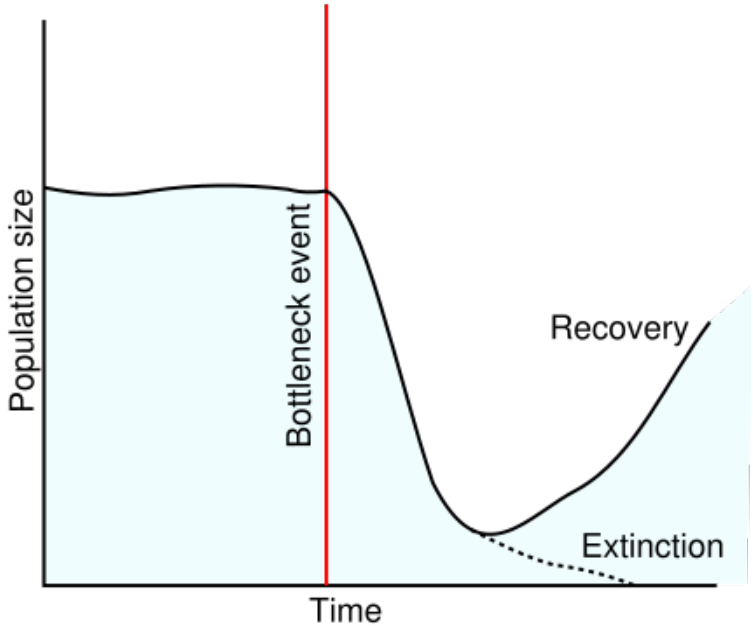

Figure 13.17: A random but major catastrophe which causes a sudden, severe reduction in population can lead to a bottleneck effect. The reduction in gene pool size - and often diversity - leaves populations subject to genetic drift; chance variations can cause extinction – or accelerated evolution leading to recovery. Even if recovery occurs, genetic diversity remains low.

Figure 13.18: The Northern Elephant Seal population fell to fewer than 100 individuals due to overhunting during the 19 century. Although their numbers have recovered, the bottleneck effect of reduced genetic variation limits their potential to adapt to future environmental changes.

their potential to adapt to changing environments.

Figure 13.19: Although the cause is unknown, South African Cheetahs apparently experienced a population bottleneck 10,000 years ago. Their current genetic uniformity is remarkable; skin grafts between even unrelated individuals do not elicit rejection responses.

We humans may have experienced a population bottleneck between 70,000 and 75,000 years ago, when supervolcano Mount Toba exploded with category 8 ("megacolossal!") force in Sumatra. According to anthropologist Stanley Ambrose's theory, global temperature dropped as much as 5 degrees Celsius for several years, possibly leading to an ice age. Ambrose believes that the environmental effects ("six years of relentless volcanic winter") reduced the total human population to less than 10,000, and that isolated individual populations would have experienced genetic drift and rapid evolution or extinction.

The Founder Effect

Whereas a drastic reduction in population size causes the bottleneck effect, a form of population expansion leads to the **founder effect.** If a small group of individuals (the founders) breaks off from a larger population to colonize a distant area, they will probably carry with them only a limited amount of the genetic diversity of the original population (**Figure** 13.20). For this reason, the new population they establish may differ significantly in genotype and phenotype. Inevitably, it will also be small and therefore subject to genetic drift.

On newly formed islands, such as the Galapagos, Hawaii, and more recently Surtsey, Iceland, founder populations are often the only source of life on the island. Many founder populations probably become extinct, but others evolve rapidly, due to genetic drift. Some may diverge

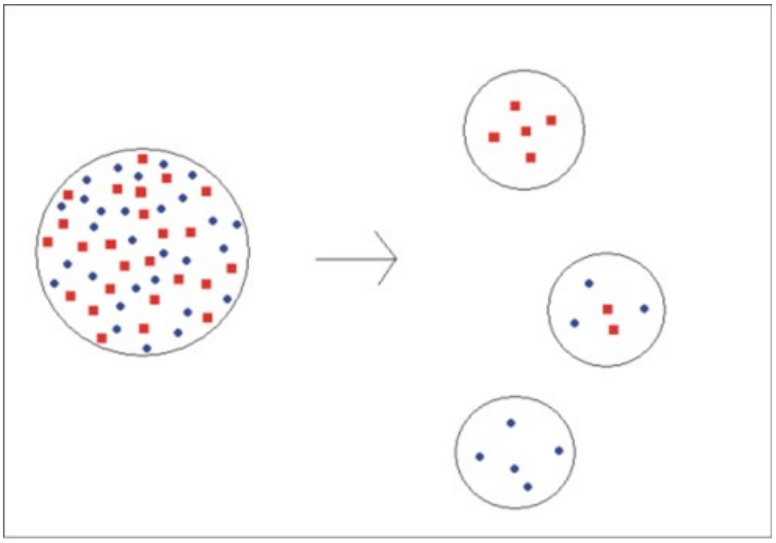

Figure 13.20: In this diagram, the red squares and blue dots represent individuals with different alleles. Small groups of individuals (see the right three circles) which leave a larger population (left) to colonize a new area carry with them smaller gene pools with allele frequencies which may differ significantly from that of the parent population – due to chance. The effects of chance in these new populations become more important; genetic drift may result in extinction or rapid evolution.

rapidly to occupy many available ecological niches – a process known as **adaptive radiation.** As we have discussed in past chapters, Galapagos finches and Hawaiian honeycreepers probably each evolved from small populations of a single ancestral finch-like species (see the previous chapter on *Evolutionary Theory*).

Historically and even today, human populations have experienced founder effects. In some cases, migration and colonization are the cause. Quebec was founded by a group of no more than 2,600 people, ancestors of today's more than 7 million Quebecois, who show remarkable genetic similarity and a number of heritable diseases, well studied by geneticists.

Cultural isolation, as well as colonization, can result in founder effects. Amish populations in the United States have grown from an initial group of about 200 immigrants, dating back to the mid-1700s. Because they have remained culturally and reproductively isolated from non-Amish Americans, they show considerable uniformity. The Amish today are often studied for their genetic uniformity, as well as certain recessive conditions. Geneticists believe that just one or two of the initial 200 Amish carried a recessive allele for Ellis-van Creveld syndrome (short limbs, extra fingers, and heart anomalies), yet through genetic drift, the isolated Amish population now has the highest incidence of this syndrome in the world (**Figure** 13.21).

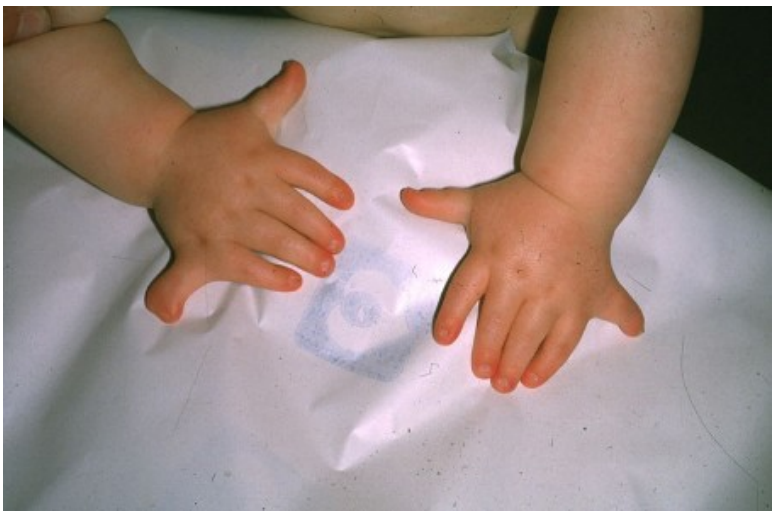

Figure 13.21: Polydactyly (extra digits) and short limbs are characteristics of Ellis-van Creveld syndrome, a genetic disease which is rare worldwide but more common in the Amish population. Because the Amish population began with just 200 immigrants and has remained isolated, their high incidence of this syndrome may be a result of the founder effect.

Natural Selection

While genetic drift, including the bottleneck and founder effects, can cause microevolution (generational change in allele frequencies), its effects are mostly random. The results of genetic drift may include enhanced capabilities, but more often, they are neutral or deleterious. Natural selection depends not on chance, but on differential survival determined by an individual's traits. Even though the variations are due to chance, the products of natural selection are usually organisms well-suited to their environment.

Recall that Hardy-Weinberg equilibrium requires that all individuals in a population are equal in their ability to survive and successfully reproduce. As Darwin noted, however, overproduction of offspring and variation among individuals often lead to differential survival and reproduction – in other words, natural selection (**Figure** 13.22). We discussed natural selection as a part of Darwin's theory of evolution in the last chapter, but in this section, we will go deeper than Darwin could. We will explore natural selection at the level of populations – in terms of allele, genotype, and phenotype frequencies.

Acting on an Organism's Phenotype

Natural selection acts on an organism's phenotype (appearance), which is a product of genotype and any environmental influences on gene expression. By selecting *for* alleles which improve survival and/or reproduction and selecting *against* harmful alleles, natural selection changes the proportion of alleles from one generation to the next – causing microevolution.

Figure 13.22: Natural selection involves (1) heritable variation (here, giraffe neck length); (2) overproduction of offspring (3 giraffes born, not all can survive); (3) differential survival and reproduction (not enough food for all giraffes; those with shorter necks starve); and (4) gradual change in traits in the population (long-necked giraffes survive and reproduce, so their genes for long necks increase in frequency in the next generation).

Let's return once more to our rabbit population. If a predator such as a hawk can see white rabbits (genotype ***bb***) more easily than brown rabbits (***BB*** and ***Bb***), brown rabbits are more likely than white rabbits to survive hawk predation. Because more brown rabbits will survive to reproduce, the next generation will probably contain a higher frequency of ***B*** alleles. Note, however, that the recessive ***b*** alleles are unlikely to disappear completely, because they can "hide" from the hawks in heterozygous brown rabbits. This is a good reminder that natural selection acts on phenotypes, rather than genotypes. The hawk - or natural selection - is unable to distinguish a ***BB*** rabbit from a ***Bb*** rabbit. Natural selection - and the hawk - is only able to distinguish a brown rabbit from a white rabbit, demonstrating how natural selection acts on the phenotype rather than the genotype of an organism.

Consider a different example, which emphasizes reproduction rather than survival: If both brown and white rabbits preferred to mate with white rabbits, the next generation's gene pool would probably show an increase in the frequency of the ***b*** allele, because white rabbits would be more likely to reproduce successfully.

Although some traits are determined by a single gene, many are influenced by more than one gene (polygenic). The result of polygenic inheritance is a continuum of phenotypic values which often show a bell curve pattern of variation. **Figure** 13.24 shows the effect of three genes, each having two alleles, on human skin color; the result is a normal distribution ranging from very dark to very light, with a peak near the middle. You can demonstrate polygenic inheritance (probably with some environmental influence) for height, ear length, or handspan by measuring your classmates and graphing the data in a similar fashion. Some curves will be flat, and others sharp – but most will resemble the normal "bell" shape.

Given this pattern of phenotypic variation, natural selection can take three forms (**Figure** 13.23). We will use the theoretical human skin color distribution **Figure** 13.24 to illustrate the three types of selection. **Directional selection** shifts the frequency curve away from the average by favoring individuals with an extreme form of the variation. The skin of early humans living in sun-rich Africa received high levels of UV radiation, which destroys vitamin B (folate) and leads to severe birth defects such as spina bifida. Selection, then, favored darker-skinned individuals, and the frequency of the darker alleles increased. After several generations, the curve would still be bell-shaped, but it would have shifted to the right, in the direction of the darker alleles. The average individual would have had darker skin as result of this microevolutionary change.

Natural Selection and Human Migration

As humans migrated into the northern hemisphere, excessive UV radiation was no longer a problem, but the relative lack of sunlight led to lower levels of vitamin D_3, normally synthesized in the skin and necessary for calcium absorption and bone growth. Thus, selection in the north favored lighter-skinned individuals – by itself another example of directional selection. However, if we consider the human population as a whole at that time, **disrup-**

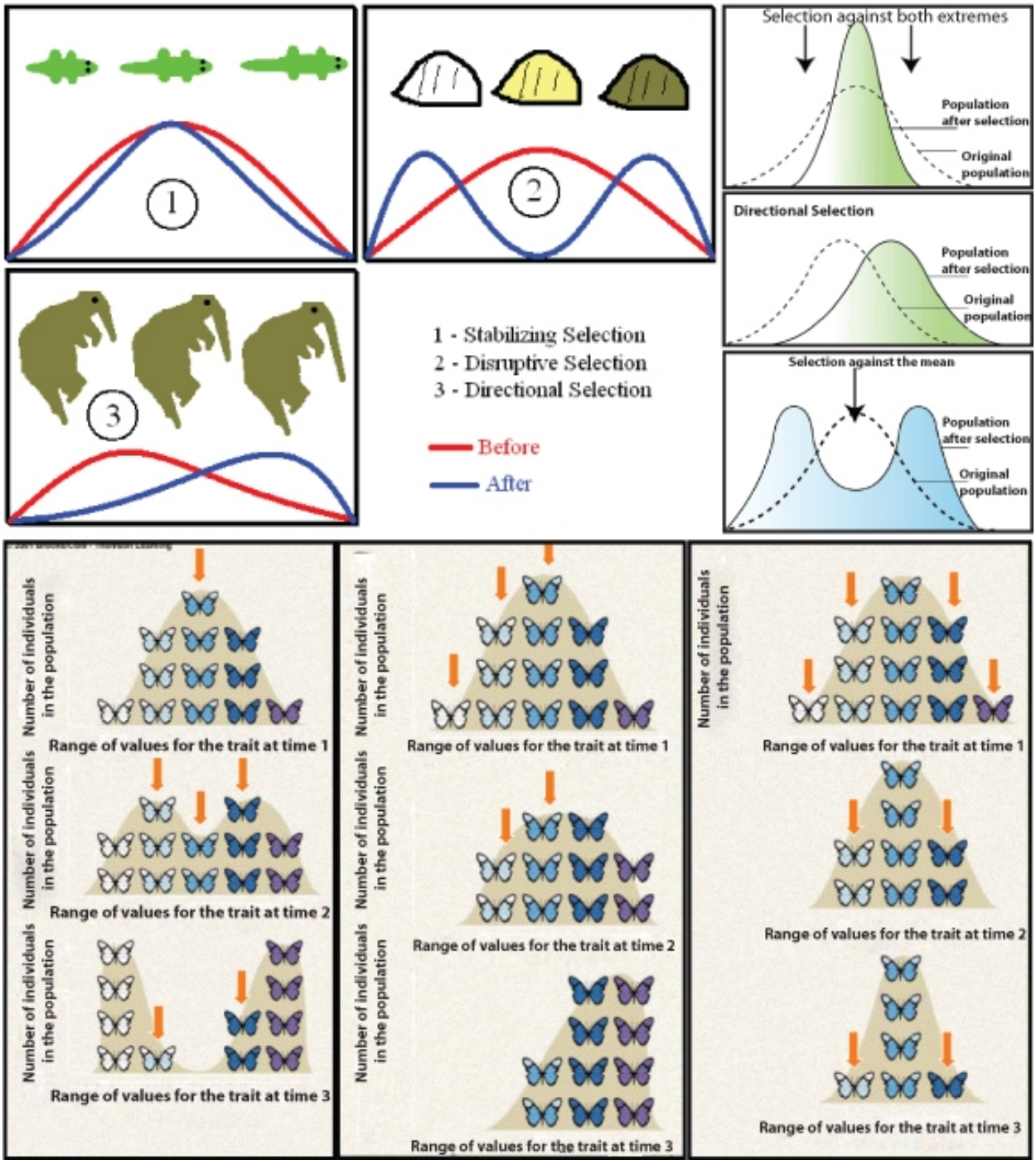

Figure 13.23: Three types of selection can alter allele frequencies, causing microevolution. The effect of stabilizing selection (1) is to reduce variation. Disruptive selection (2) results in two different populations, which may eventually be isolated from one another. Directional selection (3) enhances or reduces a single characteristic, such as trunk or snout length in the above example.

tive selection would describe the microevolution taking place. In northern climates, alleles for light skin would be favored, and in southern climates would select for alleles for dark skin, resulting in two distinct peaks in the distribution of skin color phenotypes and their corresponding genotypes. Keep in mind that the "three gene – dark/light" model is an over-simplification of the genetics underlying skin color, but the adaptive values are real, and the model allows us to illustrate how microevolution works. Note that a map of human skin colors supports this type of selection to some extent (**Figure** 13.24).

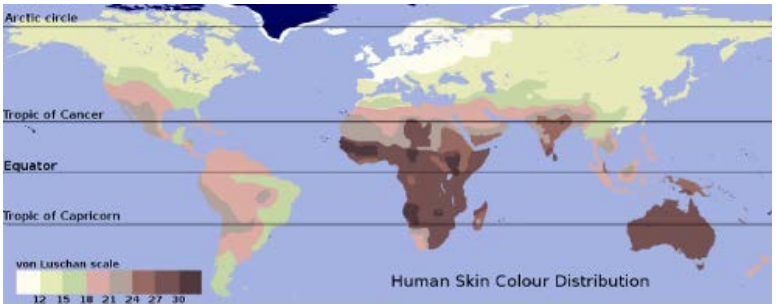

Figure 13.24: The distribution of skin colors at least partially supports disruptive selection – for lighter skin in the north, to allow sunlight to form vitamin D in the skin, and for darker skin toward the equator to prevent UV radiation from breaking down vitamin B-folate.

Today, extensive migration, mobility, and intermarriage in the human population may be changing selective pressures on skin color once again. For the sake of argument, let's make the somewhat unrealistic assumption that mixing becomes complete and that all people will be sufficiently mobile that they experience intermediate levels of sunlight. These conditions would select against both extremely dark skin (too little vitamin D_3) and extremely light skin (too little vitamin B-folate). The result would be a taller, narrower distribution – less diversity - about the same mean, a phenomenon known as **stabilizing selection**. Although our example is perhaps unrealistic, stabilizing selection is probably the most common form of natural selection, preventing form and function from straying away from a "proven" norm.

Stabilizing Selection

Stabilizing selection can lead to the preservation of harmful alleles. A famous example, which we considered in earlier lessons, is sickle-cell anemia. The gene for Beta-hemoglobin - half of the oxygen-carrying protein in our blood - has two alleles, which we will call Hgb-A and Hgb-S. Individuals having two copies of the Hgb-S allele suffer from sickle-cell anemia, a potentially lethal disease in which sickled cells clog capillaries and cannot carry oxygen efficiently. In equatorial regions, individuals with two copies of Hgb-A become infected with *Plasmodium* parasites and often die from malaria. However, individuals with one copy of each allele (the heterozygous genotype) escape both causes of death; although they may experience slight sickling at high altitudes, they do not suffer from full-blown anemia, and

malaria parasites cannot infect their red blood cells. Stabilizing selection has maintained the frequencies of both alleles, even though each is potentially lethal in the homozygous state.

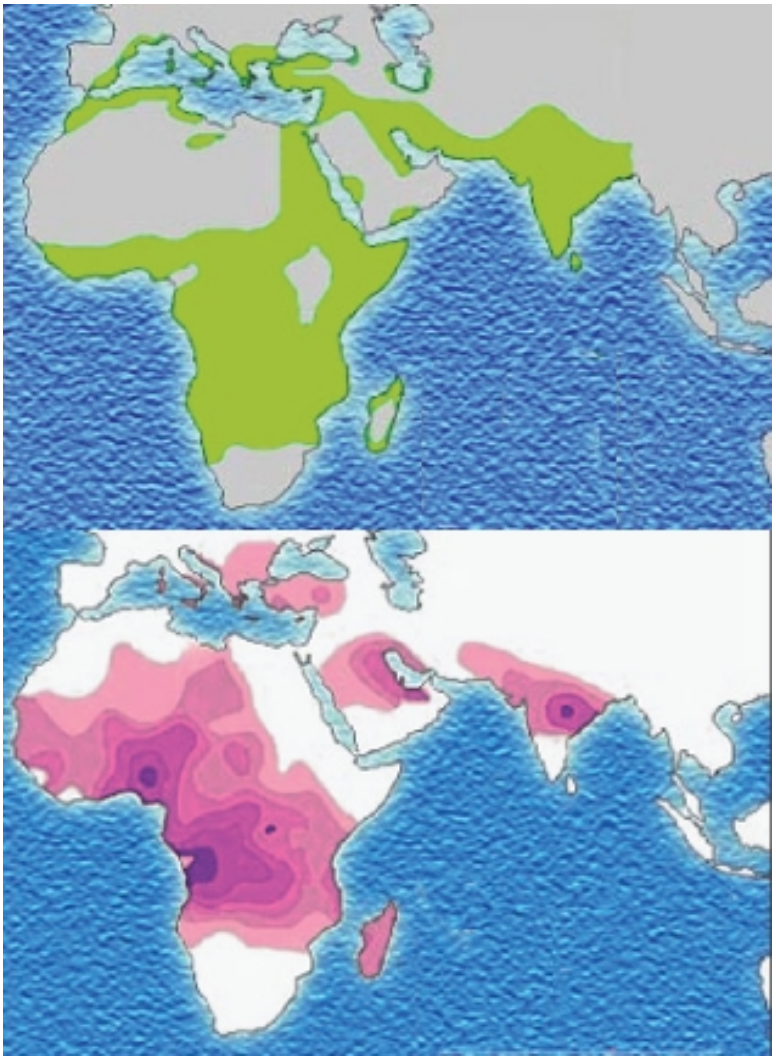

Figure 13.25: The distribution of malaria (top) correlates closely with the distribution of the sickle-cell allele (bottom). Because the heterozygous genotype confers immunity to malaria, this allele which is lethal in the homozygous condition persists in environments where malaria is common. Thus, natural selection can occasionally result in persistence of harmful alleles.

Selection for a particular trait may also select for other traits which do not directly affect fitness – if, for example, genes are linked, or if a single gene influences several different traits.

Fitness

Another way to look at natural selection is in terms of **fitness** - the ability of an organism with a certain genotype to reproduce. Fitness can be measured as the proportion of that organism's genes in all of the next generation's genes. When differences in individual genotypes affect fitness, the genotypes with higher fitness become more common. This change in genotype frequencies is natural selection.

Kin Selection

An intriguing corollary of genotype selection is **kin selection.** Behaviors which sacrifice reproductive success or even survival can actually increase fitness if they promote the survival and reproduction of close relatives who share a significant proportion of the same genes. Examples include subordinate male turkeys, who help their dominant brothers display to potential mates (**Figure** 13.26) and honeybee workers, who spend their lives collecting pollen and raising young to ensure that their mother, the queen, reproduces successfully (**Figure** 13.27).

Figure 13.26: Wild turkeys display in groups of closely related individuals, but only alpha males eventually mate. Subordinate males sacrifice their chance to reproduce, even chasing away other males to promote their dominant brothers' success, because this behavior increases the chance that the genes they share will be represented in the next generation. This means of increasing gene frequency is kin selection.

We have looked carefully at equilibrium populations and at possible disruptions of equilibrium which cause microevolution – a generational change in a population's allele frequencies:

- Mutation, which together with sexual reproduction is the ultimate source of variation,

Figure 13.27: Many social insects also illustrate kin selection. These honeybee workers are sterile. They spend their lives collecting pollen, feeding larvae, and cleaning and defending the hive. With no chance of reproductive success of their own, they dedicate their lives to the reproductive success of the hive's queen – their mother – who shares 50% of her genes with each of them.

and is an important cause of microevolution in microorganisms
- Gene flow, which can accelerate microevolution by importing new, already successful alleles
- Genetic drift, which can increase the effect of chance variations in small populations
- Natural selection, which can be directional, disruptive, or stabilizing
- Specialized types of selection, such as mate selection and kin selection

Evolutionary biologists are not yet in agreement regarding the relative importance of each type of selection to the history of life, although most would agree that natural selection is the primary force in microevolution. In the next lesson, we will apply our understanding of microevolutionary processes to that "mystery of mysteries," as Darwin and Herschel called it: the origin of species.

Lesson Summary

- Macroevolution – change in species over geologic time – is the cumulative effect of microevolution.
- Microevolution – evolution within species or populations – can be measured as a generation-to-generation change in allele frequencies.

- Non-evolving populations have constant frequencies of alleles and genotypes – genetic equilibrium.
- The Hardy-Weinberg model holds for equilibrium populations under 5 conditions:

1. no mutation
2. no migration
3. very large population size
4. random mating
5. no natural selection

- A generalized form of the Hardy-Weinberg equation for a gene pool of two alleles at equilibrium is:

Table 13.3:

p^2	+	2 pq	+	q^2	=	1
frequency of genotype BB		frequency of genotype Bb		frequency of genotype bb		

where p is the frequency of one allele and q the frequency of the other allele.

- In nature very few populations meet the Hardy-Weinberg requirements for equilibrium, due to constant mutation, gene flow, small populations, nonrandom mating, and environmental change.
- Random, spontaneous mutations constantly generate new alleles in a gene pool, destabilizing genetic equilibrium and creating the potential for adaptation to changing environments.
- In multicellular organisms, only mutations that affect germ cells become part of the gene pool.
- Because of extensive "junk" DNA, repair enzymes, and multicellularity, many mutations do not reach the gene pool.
- Many mutations are harmful, disrupting protein function.
- Because the genetic code is redundant and some amino-acid substitutions may not change protein function, many mutations have no effect on an organism's fitness.
- Even neutral mutations hold potential for future selection if the environment changes.
- A few mutations may be advantageous, improving or changing protein function.
- In microorganisms mutation rates are much higher due to rapid reproduction and small genomes.
- Mutation, together with recombination of existing alleles provides the diversity which

is the raw material for natural selection and evolution.
- The movement of genes from one population to another (gene flow) can change allele frequencies.
- Gene flow can accelerate the spread of successful alleles or reduce differences between populations.
- In small populations random variations in allele frequencies can significantly influence the "survival" of any allele, regardless of its adaptive value; this phenomenon is genetic drift.
- Genetic drift can result in extinction of an allele or an entire population.
- Alternatively, genetic drift can lead to rapid evolution of a population.
- In the bottleneck effect, a catastrophe or disease or overhunting dramatically reduces a population's size and genetic variation, increasing its susceptibility to the effects of genetic drift.
- In the founder effect, a small group leaves a larger population to colonize a new area. Again, genetic drift may lead to loss of genetic diversity, extinction, or rapid evolution.
- Genetic drift leads to evolution in populations of small size, but results are mostly due to chance.
- Natural selection occurs in populations of any size, and results are more likely to adapt a population to its environment.
- Natural selection acts on phenotype variations, so may include environmental effects which are not heritable.
- Evolution is a result of natural selection, and is measured as a change in allele frequencies.
- For a trait whose genetic basis is polygenic, the pattern of phenotypic variation usually forms a bell curve about an average value.
- Directional selection results in a shift of allele frequencies toward one extreme.
- Disruptive selection favors both extremes over the average phenotypic value.
- Stabilizing selection maintains or narrows existing variation in phenotype.
- **Fitness** is the ability of an organism with a certain genotype to reproduce successfully.
- Because alleles often affect more than one trait in different ways, or have different effects in different environments, natural selection can sometimes lead to the persistence of harmful or even lethal allele.
- Kin selection involves the sacrifice by an individual of his/her reproductive potential in order to help a close relative reproduce successfully.

Review Questions

1. Define microevolution in terms of allele frequencies.
2. Describe genetic equilibrium, including the Hardy-Weinberg conditions.
3. In the United States, about 1 in every 12 black people of African descent carry one copy of the allele for sickle-cell anemia. Assuming the five conditions of Hardy-Weinberg equilibrium hold (we'll consider why they probably don't in question #4), calculate

the probability that a member of the next generation will suffer from sickle-cell anemia (have the homozygous Hemoglobin S genotype).

4. Discuss the reasons why the 5 conditions for Hardy-Weinberg equilibrium are probably not met by the black population for the Hemoglobin alleles.
5. Analyze the possible effects of mutation, and the probability and importance of each.
6. Describe two possible effects of gene flow on the genetics of a population.
7. Describe three possible effects of genetic drift on populations and/or specific alleles.
8. Why do we consider Northern Elephant seals endangered, even though their population has risen to 100,000 individuals?
9. Use the distribution of phenotypes for a trait whose genetic basis is polygenic to interpret directional, disruptive, and stabilizing patterns of selection.
10. Describe how natural selection can sometimes lead to the persistence of harmful or even lethal allele. Include an example.

Further Reading / Supplemental Links

- "The Gene School:"
- http://library.thinkquest.org/19037/population.html
- http://genetics-education-partnership.mbt.washington.edu/class/activities/HS/sickle-bean.htm
- http://www.koshland-science-museum.org/teachers/idactivity-act018.jsp
- http://chroma.gs.washington.edu/outreach/genetics/sickle/index.html
- http://www.umsl.edu/~biology/hwec/MO-STEP/lessons/naturalsel.html
- http://www.radford.edu/~rsheehy/Gen_flash/popgen/
- http://www.phschool.com/science/biology_place/labbench/lab8/intro.html
- http://sps.k12.ar.us/massengale/lab_8_sample2_ap_population_gene.htm
- http://www.bgsu.edu/departments/chem/faculty/leontis/chem447/PDF_files/Jablonski_skin_color_2000.pdf
- https://www3.nationalgeographic.com/genographic/
- http://darwin.eeb.uconn.edu/simulations/simulations.html
- http://www.berkeley.edu/news/media/releases/2005/03/02_turkeys.shtml
- http://essp.csumb.edu/eseal/kristi_west/history.html

Vocabulary

adaptive radiation Relatively rapid evolution of several species from a single founder population to several to fill a diversity of available ecological niches.

allele frequency The fraction (usually expressed as a decimal) of a population's gene pool made up of a particular allele.

bottleneck effect The loss of diversity resulting from a drastic reduction in population size and subsequent genetic drift.

directional selection Selection which favors one side of a phenotypic distribution – one allele or one extreme of a normal distribution.

disruptive selection Selection which favors the two extremes of a phenotypic distribution – the ends of a bell curve, or the homozygous phenotypes, as opposed to the average, or heterozygous phenotype.

fitness The ability of an organism with a certain genotype to survive and reproduce, often measured as the proportion of that organism's genes in all of the next generation's genes.

founder effect The loss of genetic diversity resulting from colonization of a new area by a small group of individuals which have broken off from a larger population.

gene flow The net movement of genes into or out of a population through immigration or emigration.

genetic drift Random changes in allele frequencies in small populations.

genetic equilibrium State of a population in which allele and genotype frequencies remain constant from one generation to the next – a non-evolving population.

Hardy-Weinberg model Describes a population at genetic equilibrium, meeting five conditions: no mutation, no migration, very large population size, random mating, and no natural selection.

kin selection Behaviors which sacrifice reproductive success or even survival to promote the survival and reproduction of close relatives who share a significant proportion of the same genes.

macroevolution Evolution at or above the species level.

microevolution Evolution within a species or population, also defined as a generation-to-generation change in allele frequencies for a population.

mutation A change in the nucleotide sequence of DNA or RNA.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

polygenic trait Traits that are influenced by more than one gene.

stabilizing selection Selection which favors the average or heterozygous phenotype, resulting in no change or in a narrowing of the distribution of phenotypes.

Points to Consider

- This lesson discussed probable past microevolution of alleles for genes for human skin color and hemoglobin. For what other genes (or heritable traits) can you suggest past selective pressures? Do you think certain human genes (or heritable traits) may be at genetic equilibrium? Give some examples, and explain your reasoning.
- Some people suggest that we humans have removed ourselves from natural selection. Do you agree?
- What are some consequences of understanding that chance variations and natural selection can result in the persistence of lethal alleles, such as the alleles for sickle-cell anemia and cystic fibrosis?
- Do you think it is important that people understand the biological basis of skin color? Explain

13.3 Lesson 13.3: The Origin of Species

Lesson Objectives

- Recognize that new discoveries since Darwin have added an understanding of speciation to evolutionary theory.
- Explain the concept of a species.
- Define the biological species concept and analyze its usefulness.
- Compare the biological species concept to morphological, genealogical, and ecological concepts.
- Analyze the reasons why biologists consider all humans to be members of the same species.
- Define speciation.
- Describe two conditions that can lead to speciation.
- Explain the results of speciation in terms of adaptation, chance, and changes in the environment.
- Distinguish allopatric from sympatric speciation.
- Describe an experiment which demonstrated allopatric speciation.

- Describe two general types of reproductive isolation.
- Explain how polyploidy can result in sympatric speciation.
- Discuss the use of hybridization to form new crop species.
- Analyze the importance of environmental complexity to sympatric speciation for animals.
- Compare and contrast the gradualist and punctuated equilibrium models of evolutionary change.
- Describe conditions that could increase the rate of speciation.
- Describe circumstances that could lower the rate of speciation.

Species Concept

Darwin avoided the use of the word evolution in his major work about evolution. The word "evolve" appears once, at the very end. He titled his work *The Origin of Species* – a process or group of processes now called **speciation.** What exactly is a species? How did the millions of species which exist on earth today arise? Will they (we!) continue to change? How quickly? These are questions Darwin sought to answer – and the questions we will explore in this lesson on evolution. Darwin's work opened the door to life's history. This lesson will look at the details and modifications of his ideas which research has made clear in the 150 years since he published *The Origin*.

What is a Species?

A toddler readily recognizes that she/he is surrounded by distinct groups of individuals which we call "kinds" of plants and animals. Biologists refer to kinds of living things as a **species** - groups of individual organisms which are very similar. If we look closely, however, variations make it quite difficult to decide where to draw the lines between species. For example, are a St. Bernard and a Chihuahua similar enough to group within the same species? Just how similar must two organisms be for biologists to decide they are members of the same species? The answer to this question is not clear, even to biologists who specialize in classification. We will explore several, because how we define a species can help to clarify how species develop.

The Biological Species Concept

A widely used definition of species is the **biological species concept** (**Figure** 13.28), first proposed by evolutionary biologist Ernst Mayr in 1942. Mayr's concept begins with the idea that members of a species must be *similar enough that they could interbreed.* Because all dogs - from a St. Bernard to a Chihuahua – are capable of interbreeding, biologists consider all dogs to be members of the same species. If you are familiar with mules, however, you know that this definition needs clarification. If horses and donkeys mate, they produce mules, but

mules are sterile and cannot continue to interbreed. Therefore, the biological species concept becomes *organisms similar enough to interbreed and produce fertile offspring.* Horses and donkeys, therefore, are not members of the same species. As you may know, wolves and dogs can interbreed to produce viable hybrids with fertile offspring; surely, wolves and dogs are not members of the same species? The last part of the definition addresses this problem, and the complete definition becomes:

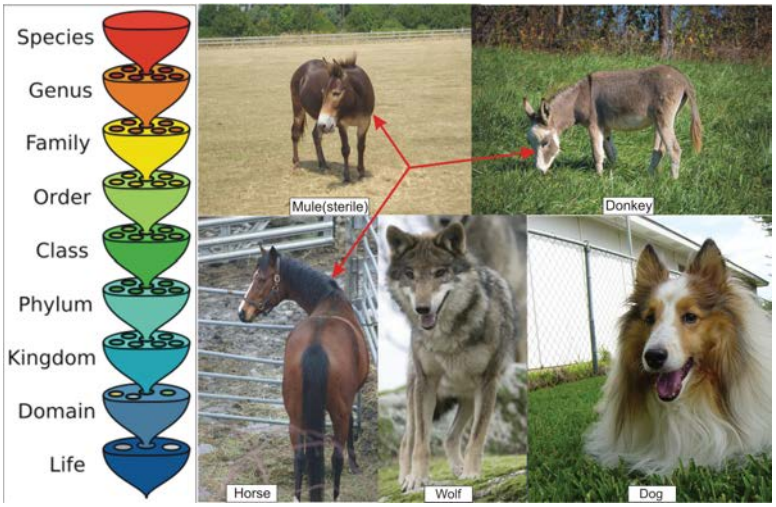

Figure 13.28: The species is the smallest group or level used to classify living things. As for all levels, the goal of classification is to show evolutionary relationships. A biological species is defined as a group of organisms similar enough to reproduce and have fertile offspring under natural conditions. A mating between a horse and a donkey produces a mule, but the mule is sterile, so the horse and donkey are not considered members of the same species. On the other hand, dogs and wolves can interbreed successfully, but because they do not do so in nature, they are not classified as members of the same species.

A **biological species** is a group of organisms similar enough that they could interbreed and produce fertile offspring *under natural conditions.*

This definition serves the goal of defining members of a species as individuals which are still undergoing evolution – they form a distinct yet potentially common gene pool. You will learn much more about classification in the next chapter, but here it is important to realize that one of the primary goals of classification is to show evolutionary history – patterns of common ancestry. This makes the biological species – a functionally reproducing unit – an important foundation of classification. Closely related species descended from relatively recent common ancestors, and distantly related species descended from more distant common ancestors. The emphasis the biological species concept places on successful reproduction fits this goal of classification quite well.

Another advantage of the biological concept is that it has the potential to explain how speciation occurred – that is, how two closely related groups of organisms became different

species through **reproductive isolation**. Members of two species may appear very similar, yet fail to interbreed because of **reproductive barriers**. Barriers to reproduction may either prevent mating, or prevent development of a fertilized egg after mating. Elaborate courtship behaviors, including the blinking pattern of fireflies or the songs of birds, are often required to elicit mating behavior – and limit mating to members of a species (**Figure** 13.29). Different breeding seasons, such as flowering dates, can also prevent interbreeding. Molecular differences between even closely related species may prevent sperm or pollen from actually fertilizing eggs. Once the eggs are fertilized, chromosomes may be so incompatible that mitosis and meiosis cannot proceed normally; if the zygote cannot develop, offspring do not survive. All of these barriers between species work to ensure successful reproduction within species, keeping specific, useful adaptations "in the family," so they are a logical way for us, too, to distinguish members of one species from members of another.

Figure 13.29: The Western Meadowlark (left) and the Eastern Meadowlark (right) appear morphologically identical. However, geography and songs serve as reproductive barriers to interbreeding, so the two are considered to be separate species.

Although the biological species concept is extremely helpful in evolutionary thinking it has serious limitations for practical use. For organisms that reproduce asexually – including all bacteria and viruses - the definition is entirely unworkable. Nor can we detect whether or not fossil organisms would have been able to interbreed – whether or not they coexisted. Biologists must rely on structure and (if available) biochemical similarities to classify fossils and most microorganisms.

The Morphological Species Concept

Alternatives to the biological species concept emphasize the characteristics and processes which unite, rather than divide (reproductive barriers), species. We will look at just a few in order to gain insight into evolutionary thought. A much more practical definition is the **morphological species concept**, which groups organisms based on structural and biochemical similarities. Recent advances in molecular biology, such as DNA comparison, have strengthened this means of clarifying evolutionary relationships. Biologists probably use this method more than any other to differentiate species in nature, despite its limitations in confirming the potential for interbreeding.

The Ecological Species Concept

The **ecological species concept** focuses on a group's common **ecological niche** – the set of environmental conditions and resources used or required by the group. This concept is based on the idea that ecological and evolutionary processes divide resources in such a way that *individuals can most efficiently adapt* to use those resources *as a group*. All members of a species, then, have a unique set of adaptations to a particular set of environmental conditions. Note that both the morphological and ecological definitions "work" for asexually reproducing organisms, and many fossils, as well. However, they do not help to explain *how* two closely related groups became different species, as does the biological definition.

The Evolutionary Species Concept

The last concept we will consider has the potential to clarify the path of speciation, or evolutionary history – that primary goal of classification. The **genealogical** or **evolutionary species concept** defines a species as a group of organisms with a unique genetic history – a group which shares common ancestry without divergence. A species, according to this concept, is a group which forms one tip on the branching tree of life's history. Modern technology which compares DNA and protein sequences makes this definition workable, but still, the mechanism of speciation is not defined.

Ideally, all of these ways of determining exactly which individuals make up a species would merge; all make valid points about the idea of a species, and all seek the common goal of defining a new, unique unit of life in space and time. Practically, however, each has its own usefulness for different purposes. If we were working in the field, we would undoubtedly use the morphological concept. However, as we explore the idea of speciation mentally and through lab models, we will adopt the biological species concept as our working definition.

Figure 13.30: All humans are members of the same biological species. All races and cultures can and do intermarry, and our DNA is 99.9% identical.

Humans, One Species?

What about humans? Are we all members of the same species? According to the biological species concept, the answer is a resounding yes. Despite our differences in appearance, culture, and location on planet Earth, any human female is capable of producing fertile offspring with any human male. Therefore, all humans are members of the same biological

species (**Figure** 13.30). In contrast, humans and chimpanzees do not interbreed even when they share the same territory, so biologists consider chimpanzees to be a distinct species. Before we leave the "species problem" and *Homo sapiens*, it is worth noting that *all* of the various definitions of species confirm the unity of the human species. DNA sequences, cell chemistry, anatomy, ecological resources, and reproductive ability all reveal similarities which unite us as a single species with common ancestry. In fact, the most recent and precise method of comparison – DNA sequences – shows that somewhere between 1 in 100 and 1 in 1,000 base pairs differ, on average, between one human and the next. Based on this analysis, we humans are 99.9% identical. The differences which seem so great to us (skin color, facial features, build, personality) are important for recognition of individuals, and a few may adapt us to particular regions of the Earth, but overall, we are vastly more similar to than different from each other; we are one species.

Although we may not learn exactly how we came to be a separate species, we can gain some insight by looking closely at what is known of the process of speciation. What do we know now – that Darwin did not know - about "the origin of species"?

An Overview of Speciation

Speciation occurs at the boundary between microevolution and macroevolution. At what point do the allele frequency changes of microevolution add up to define a new and separate species?

Ernst Mayr, who developed the biological species concept mentioned above, also identified two essential components of speciation. For two populations to evolve into separate species, they must experience:

1. Isolation
2. Genetic divergence

Isolation limits gene flow which would tend to maintain uniformity between the two populations. Physical separation by a barrier limits migration and prevents interbreeding, but differing environmental conditions may also provide a form of isolation. Isolation increases the chance that two populations will take separate microevolutionary pathways. Returning to our white and brown rabbits, even a difference in altitude and thus temperature might separate two parts of a population so that albino individuals will be favored higher on a mountain where snow frequently accumulates, but brown individuals would be favored down toward the valleys, where snow rarely covers the ground.

Although the two rabbit populations might be isolated by environmental differences, they would not become separate species unless enough genetic differences accumulate to prevent successful interbreeding. *Genetic divergence* is more likely if populations are small, increasing the chance of genetic drift. Even in large populations, however, environmental

differences may result in large genetic differences which prevent interbreeding. In our rabbit populations, for example, selection for white rabbits might be accompanied by mate selection based on white coat color. If mate preferences were heritable and sufficiently strong, interbreeding between the brown population and the white population would cease, and the two populations would become two species.

The result of speciation is two groups of individuals, each more closely adapted to local environmental conditions than the larger parent population. Although speciation may not always result in a better fit between a species and its environment (remember that genetic drift increases the influence of chance), over time, natural selection tends to increase fitness. A species' adaptations to both physical and living environments increase the chance that the species will survive. The millions of species which exist today are each carefully attuned to a particular niche. And, just as variation within a species ensures that some individuals will survive environmental change, a great diversity of species increases the chance that at least some organisms will survive major changes in the environment.

Isolation and genetic divergence are both prerequisites for speciation, but they are so closely related that sometimes it is difficult to distinguish one from the other. Physical isolation may encourage genetic divergence, but many evolutionary biologists believe that reproductive isolation can result from genetic divergence alone. That leads us to two major categories of speciation – one based on geographic isolation, and the other based on reproductive isolation alone. These two categories, and examples of speciation from each, are the topic of the next section.

Isolating Mechanisms

Biologists today divide isolating mechanisms into two major categories based on whether they happen in different locations (*allopatric* = "other fatherland") or a single location (*sympatric* = "same fatherland") (**Figure** 13.31).

Allopatric Speciation

Allopatric speciation involves geographic barriers, which physically isolate populations. Formation of a land bridge such as the Isthmus of Panama, for example, could separate members of a marine population into two groups. Emergence of a mountain range could separate members of a lowland species. According to the fossil record, the rifting of continents divided populations of terrestrial animals and plants. In these cases, dramatic changes in landforms lead to geographic isolation; however, movements of animals and plants can also result in physical isolation. Single individuals or small groups of individuals may move away from a parent population to colonize a new area, and the new colony could be isolated from its parent population. Such movements are not always intentional; a storm apparently carried a small flock of finches from the coast of South America to the Galapagos Islands.

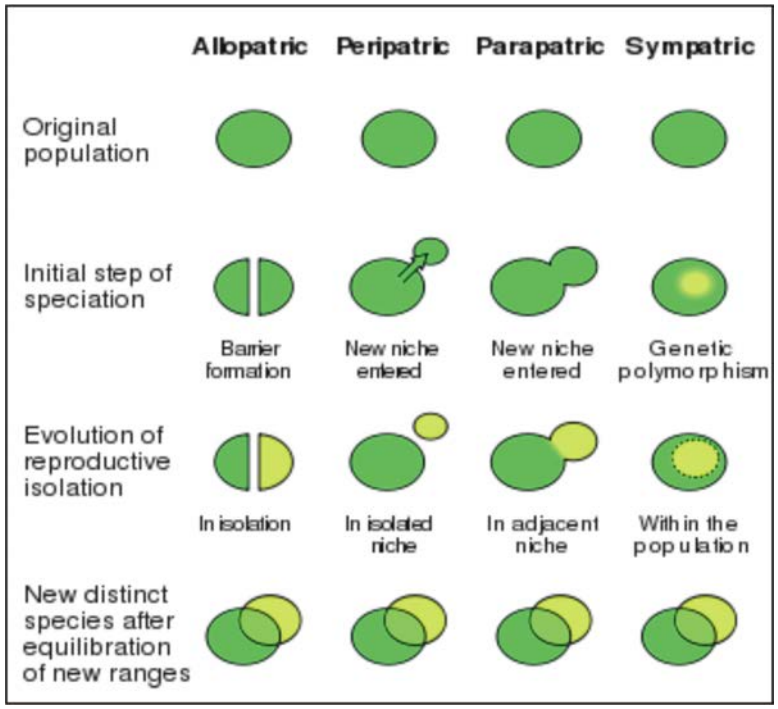

Figure 13.31: Two mechanisms of speciation are allopatric ("other fatherland") and sympatric ("together in the fatherland") forms. In both cases, a single population divides into two, and heritable differences eventually prevent gene flow between the two through reproductive isolation.

In each case, geographic barriers (the land bridge, the ocean) isolate the two populations so that gene flow stops and genetic divergence can proceed. Natural selection may lead each population to adapt to its own unique environment, or genetic drift may lead to chance differences in gene pools. If genetic divergence results in reproductive incompatibility, the two populations have become two separate species.

Diane Dodd, working with a laboratory population of fruit flies (**Figure** 13.32), experimentally verified the idea that physical isolation can lead to reproductive isolation and speciation. Dodd split the population into two groups, and fed maltose to one group and starch to the other. She observed that each new environment selected for improved efficiency in digesting the available food molecule. After eight or more generations of isolation, the two populations were recombined. After isolation, "starch" flies preferred to mate with other "starch" flies, and "maltose" flies preferred "maltose" mates. Although the preferences were not absolute, they did demonstrate at least initial formation of a reproductive barrier.

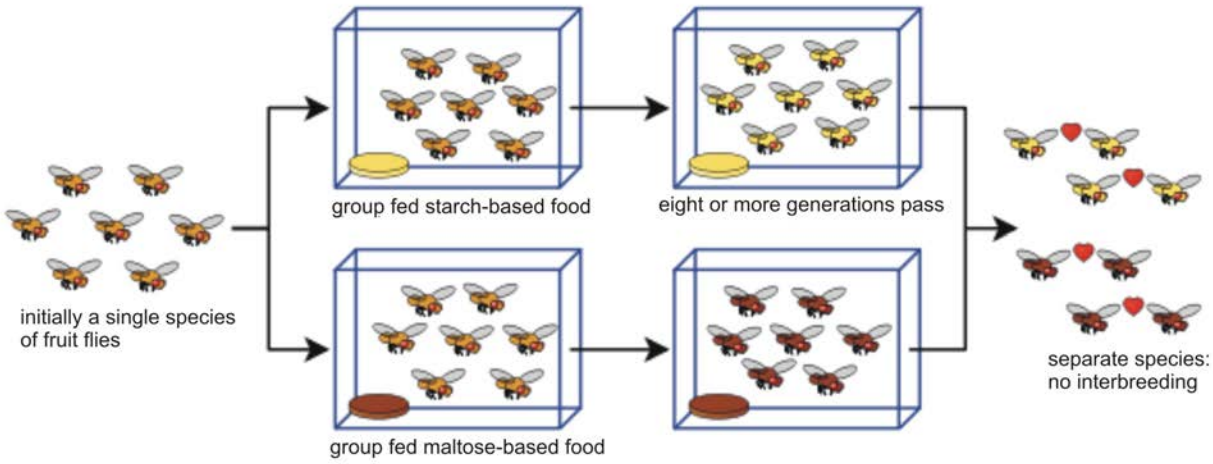

Figure 13.32: If a single population of fruit flies is divided, and the two subpopulations are separated for at least eight generations and fed different foods, members of the subgroups prefer to mate with individuals from their own feeding group. Although this behavioral reproductive barrier was not complete, Diane Dodd's data supports the hypothesis that geographic isolation can lead to heritable reproductive isolation.

Sympatric Speciation

Sympatric speciation involves the emergence of a new species within the geographic range of the parent population. In the absence of geographic isolation, reproductive barriers must arise in different ways in order for new species to form. Some biologists doubt the relative importance of sympatric speciation to evolutionary change, but several examples demonstrate the potential for this mechanism of evolution.

Polyploidy

In plants, new species occasionally arise by duplication of chromosomes – a condition known as **polyploidy** (**Figure** 13.33). Recall that our human body cells are diploid, and that egg and sperm cells are haploid. If meiosis fails to reduce the number of chromosomes, diploid sex cells result. In plants, which can self-pollinate, diploid pollen may fertilize a diploid egg, resulting in a **tetraploid** offspring. Although tetraploids may self-pollinate or interbreed with other tetraploids, they cannot successfully reproduce with their parents, because three sets of chromosomes (two from the tetraploid parent and one from the "normal" diploid parent) cannot successfully perform the intricate dance of meiosis. Peanuts, potatoes, and cotton are familiar crops that are tetraploid. Strawberries and sugarcane are octaploid (eight sets of chromosomes in each cell, compared to our two)! Polyploidy is a common form of speciation in plants in nature, as well as in agriculture.

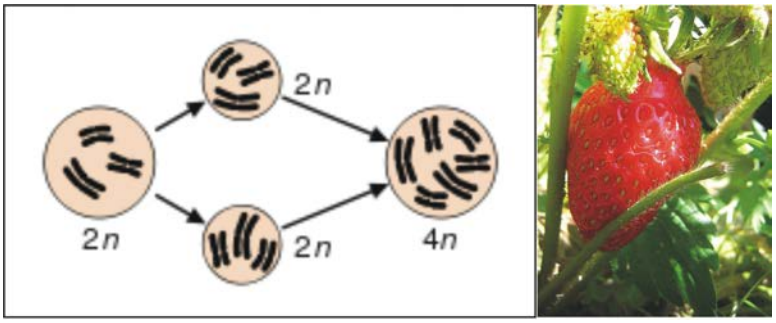

Figure 13.33: One way in which polyploidy can arise is for meiosis to produce diploid (2n), rather than haploid (1n) gametes by nondisjunction. Self-fertilization results in tetraploid (4n) offspring. Strawberries (right) probably experienced two episodes of polyploidy; they are octaploid!

Two species of plants may *hybridize* – often forming unusually vigorous **hybrid** offspring. Unfortunately, despite their vigor, these offspring are often infertile due to chromosome incompatibility. However, if polyploidy occurs within the offspring, each of the previously unmatched chromosomes has a partner, offspring fertility is restored, and a new species is formed. Triticale (**Figure** 13.34), a hexaploid hybrid of wheat and rye, was produced in the laboratory in this manner. Combining the high yield and quality of wheat with the disease-resistance of rye, triticale is now a successful grain crop in Europe, China, and Australia.

Polyploidy is less common in animals, perhaps because they less frequently self-fertilize. Some salamanders are polyploid, but offspring are usually sterile and "species" reproduce by parthenogenesis (development from unfertilized eggs). Human and other mammalian livers often contain many polyploid cells.

Although polyploidy is rare among animals, other zoological modes of sympatric speciation exist. For example, environmental change within a population's range may lead to two habitats in which genetic divergence may take place. Our hypothetical rabbit example in

Figure 13.34: Triticale (large photo and grains – inset, right) is a new crop species formed by hybridizing wheat (inset, left) and rye (insert, center). Reproduction of offspring for the new species was not possible until after polyploidy. The "final" species is hexaploid.

the last section is an example of this type of sympatric speciation. A field example involves the hawthorn fly (**Figure** 13.35), whose larval maggot stage feeds on hawthorn fruit. Apple trees, introduced to the US, often grow near hawthorns, and some hawthorn flies have begun to feed on apples. The two populations, although sympatric, have developed significant genetic differences, and at least in the wild, no longer tend to interbreed. This apparent reproductive isolation involves both temporal divergence (apples and hawthorns and their respective fly populations mature in slightly different seasons) and mating and egg-laying preferences (which link larval fruit to adult behavior). Many biologists consider these flies to be an example of sympatric speciation in progress.

Cichlid fish in East Africa's Lake Victoria illustrate both allopatric and sympatric speciation (**Figure** 13.36). Less than a million years old, the Lake harbors nearly 200 closely related cichlid species. Biologists conclude that adaptive radiation by a small group of colonizers into available niches explains the diversity of feeding specializations among these closely related species, much like Darwin's finches in the Galapagos. Because the various habitats in the huge Lake (or islands in the oceans) isolate populations before speciation, adaptive radiation is often considered a type of allopatric speciation. However, nonrandom mating may have led to at least one more recent sympatric speciation. Females of two closely related species appear to select mates based on differing, brightly colored backs. Although the two color variations can still interbreed in the lab, they do not appear to do so in nature.

Figure 13.35: The hawthorn fly (A) appears to be undergoing sympatric speciation. Traditionally, the species laid eggs on hawthorn (lower right), and the larvae (E) fed on the fruits. After the introduction of apples (upper right) to many of the same habitats, some hawthorn flies have begun laying eggs (B) on this species, and the maggots develop normally in the fruit. The two populations have diverged genetically, and no longer interbreed, at least in the wild.

Figure 13.36: Cichlids appear to have undergone tremendous adaptive radiation in the relatively new Lake Victoria in Eastern Africa. Adaptive radiation is a form of allopatric speciation. At least one pair of closely related species may also show sympatric speciation.

The Tempo of Speciation

Speciation and extinction characterize all life on earth; the fossil record clearly documents both. Two startling facts emerge from careful study of the fossil record: First, the average successful species lives for "just" a few million years. Second, over 99.9% of all species that have ever lived have become extinct. The last aspects of speciation that we will consider are the tempo and pattern of species formation.

Over time, geographic changes isolate populations. Small populations experience genetic drift. Mutations alter individual genotypes and gene pools. New habitats form, and small groups colonize them. It is clear that evolution continues to change life. However, there is considerable debate about the rate at which speciation occurs over geologic time. Most biologists agree that single mutations seldom if ever cause new species in single evolutionary "leaps." Mutations in regulatory genes, which have major effects during development, may be an exception, but in general, mutations are more likely to be harmful, and selected against. Except for the special case of polyploidy, discussed above, speciation cannot occur within a single generation. So, what do we know about the rate and pattern of speciation?

Some evolutionary biologists consider the rate of evolution to be slow and constant, with small changes accumulating to form big changes – the idea of **gradualism**. Others (Niles Eldridge and Stephen Jay Gould), in response to the apparently "sudden" appearance of new forms in the fossil record, suggest that species diverge in bursts of relatively rapid change, and then remain stable for relatively long periods – a model known as **punctuated equilibrium**. Gould maintains that speciation and evolution occur rapidly in small, peripheral populations, whereas large, central populations remain stabilized for long periods of time. It is the large, central, stable populations which are represented in our fossil record, he argues – not the small, peripheral, evolving ones. The two models are compared in **Figure** 13.37.

In either case, species require several thousand generations – which may require several thousand years – to form. Relative to the species' "lifespan" and the modest precision of our ability to pinpoint time within the geologic record, the differences between the two models may be minimal. Major characteristics of species could have evolved gradually over thousands of years, and still we would not be able to detect those changes on the geologic time scale. What we do detect are long periods of relative stability, when stabilizing selection tends to maintain equilibrium. Changes in physiology and internal anatomy could have continued during the long periods of apparent equilibrium without our seeing them; the fossil record cannot reveal these types of changes. The debate is not about the mechanism of evolution – only its tempo.

Proponents of either model admit that the pace of evolution probably changes from one set of conditions to another. Lake Victoria in East Africa, for example, is just a million years old, and yet home to more than 300 species of cichlid fish found nowhere else (return to **Figure** 13.35). Genetic analysis shows that all of them descended from a single ancestral "founder" species – relatively rapid evolution. Without competition, that species expanded across the huge Lake, and natural selection suited individual populations to exploit the many different

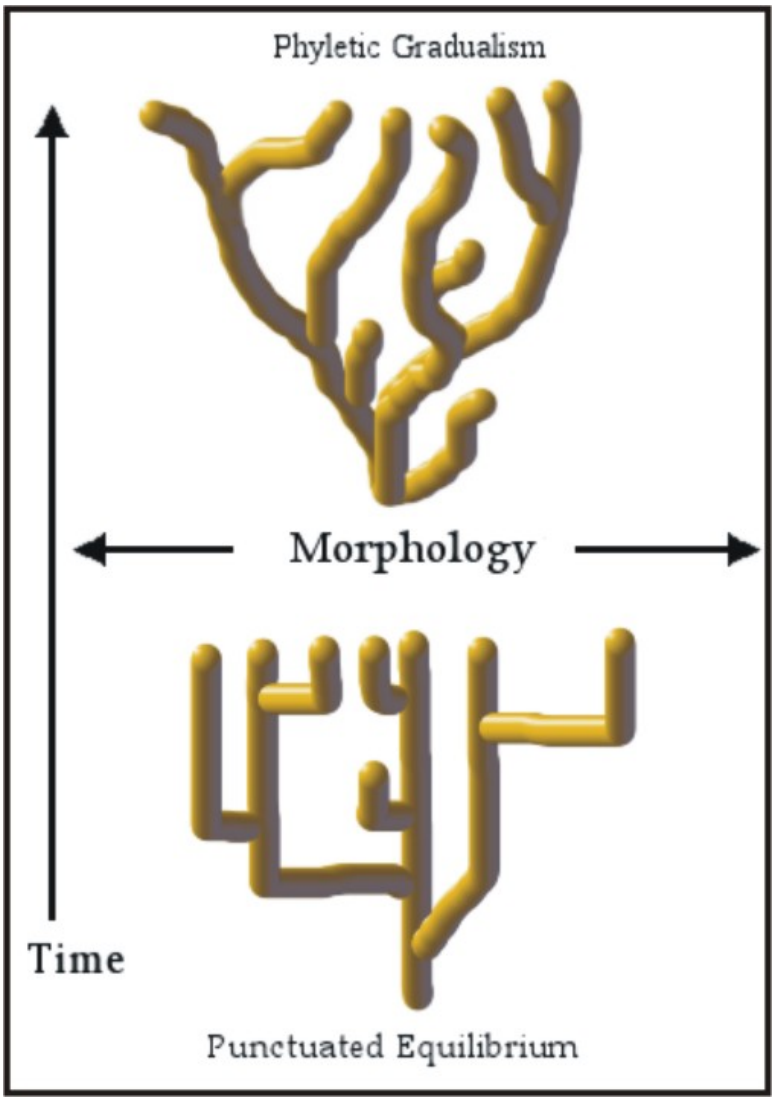

Figure 13.37: Two views of the rate at which speciation occurs: Gradualism (top) holds that small changes accumulate gradually to form big changes. Punctuated Equilibrium (bottom) suggests that rates of change accelerate over short periods (the horizontal changes in morphology which "punctuate" the tree of life) and then stabilize for relatively long periods (the vertical lines, indicating morphology is at equilibrium). To read such an evolutionary tree, keep in mind that the top represents the present: the tips of all branches which reach the top are today's species, and any branches that fail to reach the top represent extinctions.

food sources and habitats present in the Lake. Cichlid evolution is an example adaptive radiation similar to that of Darwin's finches and Hawaiian honeycreepers, discussed in the Evolutionary Theory chapter. The fossil record shows similar opportunities for accelerated evolution after mass extinctions. The extinction of the dinosaurs opened an abundance of ecological niches, soon occupied by radiating birds and mammals. Speciation may accelerate not only with a major increase in available niches, but also with the appearance of new adaptation, such as legs or wings, which allows a group to enter a variety of new niches. In contrast, long periods of environmental stability may slow the pace of speciation.

If you look back at the opening questions for this lesson, you can see that both evolution and our investigations into how evolution works are ongoing - works in progress. We have come a long way in understanding "the origin of species" since Darwin, but questions remain. Exactly what is selected - genes, genotypes, phenotypes, or individuals – is still debated; some, such as Stephen Jay Gould, accept that selection acts at multiple levels. Exactly how fast speciation occurs also remains under discussion; both gradualism and punctuated equilibrium models have merit. Several definitions of a species today serve different purposes; eventually, they should merge into a single clear picture of this basic unit of evolution.

Behind these disagreements, however, lies a powerfully reinforced theory of evolution and an increasingly detailed story of life on Earth. By any definition, humans form a single species, increasingly united by mobility, common genes, and common resources. We and the millions of species with whom we share the Earth today all arose from a single common ancestor billions of years ago – through deep time and myriad instances of allopatric and sympatric speciation. Amazing adaptive logic was most often a result of: directional, stabilizing, and disruptive environmental forces selected for favorable variations and against unfavorable ones. Chance played a major role – through mutation, gene flow, genetic drift, and much environmental change. The pace of speciation probably varied – from gradual change, to rapid change, to long periods of stability. Both speciation and extinction continue today – and will continue into the future, although we cannot predict the direction, because chance determines so much of the direction evolution takes. As a unique species, we are significantly influencing the amount of extinction – and may consequently affect the rate of speciation, as well. That, however, is a topic for a later chapter.

Lesson Summary

- Ever since Darwin's publication of *The Origin of Species*, biologists have continued to work out the details of how species originate – the foundation of evolutionary process.
- A species is the smallest group of organisms into which biologists classify living things.
- A biological species is a group of organisms that can interbreed to produce fertile offspring under natural conditions. This is probably the most widely accepted definition of a species.
- A morphological species groups organisms based on extensive structural and biochemical similarities. This is probably the most practical definition for use in the field.

- A genealogical or evolutionary species includes organisms which share a recent, unique common ancestor. This is the goal of all classification; the only question is how to recognize members.
- An ecological species groups organisms together if they share a unique set of adaptations to a particular set of environmental conditions.
- Ideally, all four definitions would merge to recognize a true species.
- All humans are members of the same biological species, because all races and cultures can and do intermarry, and our DNA is 99.9% identical.
- For populations to become separate species, they must experience isolation and genetic divergence.
- Isolation can be physical or environmental, but it must be accompanied by heritable reproductive isolation, which requires genetic divergence.
- The result of speciation is usually two groups of individuals, each more closely adapted to local environmental conditions than the larger parent population.
- Because genetic drift and environmental change increase the influence of chance, adaptation is seldom "perfect" – but over time, natural selection tends to increase fitness.
- Allopatric speciation involves geographic barriers, which physically isolate populations.
- Barriers to mating and barriers to development of zygotes can both cause reproductive isolation.
- Experiments with fruit flies support the possibility that geographic isolation can lead to reproductive isolation.
- Sympatric speciation involves the emergence of a new species within the geographic range of the parent population.
- In plants, polyploidy is a common sympatric form of "instant speciation."
- Hybridization together with polyploid has formed many vigorous crop species.
- In animals, environmental complexity may lead to sympatric speciation.
- Cichlid fish in Lake Victoria illustrate both adaptive radiation – a form of allopatric speciation – and more recent sympatric speciation due to heritable changes in mating preference.
- The Gradualism model of speciation holds that small changes accumulate to form big changes.
- The Punctuated Equilibrium model suggests that rates of change accelerate over short periods in small peripheral populations, and then stabilize for long periods in large, central populations.
- Differences between the two may be minimal, because gradual change can occur over thousands of years without our ability to detect it in the fossil record.
- Conditions that may accelerate speciation are mass extinctions and the formation of new habitat (e.g. volcanic islands) because both create a sudden availability of many "empty" niches.
- Evolution of a major new adaptation, such as legs or wings, may also accelerate speciation by suiting a species to multiple new habitats.
- Long periods of environmental stability may slow the rate of speciation.

Review Questions

1. Define the biological species concept and analyze its usefulness.
2. Compare the biological species concept to morphological, genealogical, and ecological concepts.
3. Analyze the reasons why biologists consider all humans to be members of the same species.
4. Describe two conditions that can lead to speciation.
5. Explain the results of speciation in terms of adaptation, chance, and changes in the environment.
6. Distinguish allopatric from sympatric speciation.
7. Describe two general types of reproductive isolation.
8. Describe the use of hybridization and polyploidy to form new crop species.
9. Analyze the importance of environmental complexity to sympatric speciation for animals.
10. Compare and contrast the gradualist and punctuated equilibrium models of evolutionary change. Give examples which support each.

Further Reading / Supplemental Links

Dawkins, Richard. *The Ancestor's Tale: A Pilgrimage to the Dawn of Life*. 2004. Boston: Houghton-Mifflin, ISBN 0618005838 Punctuated Equilibrium

- http://www.geocities.com/ginkgo100/pe.html
- http://www.pbs.org/wgbh/evolution/library/03/5/l_035_01.html

Phylogenetic Tree

- http://itol.embl.de/

Eastern and Western Meadowlark information, with songs - Cornell Lab of Ornithology

- http://www.birds.cornell.edu/AllAboutBirds/BirdGuide/Western_Meadowlark.html
- http://www.birds.cornell.edu/AllAboutBirds/BirdGuide/Eastern_Meadowlark.html

Adaptive Radiation of Cichlids

- http://www.current-biology.com/content/article/fulltext?uid=PIIS0960982207017046
- http://www.nature.com/hdy/journal/v99/n4/full/6801047a.html

Vocabulary

allopatric speciation The evolution of a new species from a closely related population isolated by geographic barriers.

biological species concept A group of organisms similar enough to interbreed and produce fertile offspring under natural conditions.

ecological niche The set of environmental conditions and resources used or required by a species; the role a species plays in its ecosystem.

ecological species concept A group of organisms which share a unique set of adaptations to a particular set of environmental conditions.

evolutionary species concept See genealogical species concept.

genealogical (evolutionary) species concept A group of organisms which share a recent, unique common ancestor – common ancestry without divergence.

gradualism The idea that the tempo of evolution is slow and constant, with small changes accumulating to form big changes.

hybrid Offspring of cross-breeding between two different but closely related species.

morphological species concept A group of organisms which share extensive structural and biochemical similarities.

polyploidy The duplication of chromosome sets, often resulting in "instant speciation."

punctuated equilibrium The idea that species diverge in bursts of relatively rapid change and then remain stable for relatively long periods.

reproductive barrier A condition which prevents mating or prevents the development of offspring.

reproductive isolation The separation of closely related populations by barriers to producing viable offspring.

speciation The process which results in new, separate and genetically distinct groups of organisms (species).

species See biological, ecological, genealogical, and morphological species concepts.

sympatric speciation The evolution of new species from closely related populations located in the same area.

Points to Consider

- Which definition of species – biological, morphological, ecological, or genealogical – do you prefer?
- To what extent do you think stabilizing, directional, and disruptive selection affect humans today?
- What effects might genetic engineering have on speciation?
- Do you find the evidence for sympatric speciation (the more disputed of the two forms) convincing?
- Are gradualist and punctuated equilibrium models mutually exclusive?
- Why don't disagreements about speciation threaten the theory of evolution by natural selection?

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Chapter 14

Classification

14.1 Lesson 14.1: Form and Function

Lesson Objectives

- Define taxonomy, and understand why scientists classify organisms.
- Describe Linnaean taxonomy and binomial nomenclature.

Introduction

Billions of years of evolution on Earth have resulted in a huge variety of different types of organisms. For more than two thousand years, humans have been trying to organize this great diversity of life. The classification system introduced by the Swedish botanist Carolus Linnaeus in the early 1700s has been the most widely used classification for almost 300 years.

Taxonomy

Scientific classification is a method by which biologists organize living things into groups. It is also called **taxonomy**. Groups of organisms in taxonomy are called **taxa** (singular, taxon). You may already be familiar with commonly used taxa, such as the kingdom and species. A **kingdom** is a major grouping of organisms, such as plants or animals. A species includes only organisms of the same type, such as humans (*Homo sapiens*) or lions (*Panthera leo*). The modern biological definition of a **species** is a group of organisms that are similar enough to mate and produce fertile offspring together. In a classification system, kingdoms, species, and other taxa are typically arranged in a hierarchy of higher and lower levels. Higher levels include taxa such as kingdoms, which are more inclusive. Lower levels include taxa such as species, which are less inclusive.

This type of hierarchical classification can be demonstrated by classifying familiar objects. For example, a classification of cars is shown in **Figure** 14.1. The highest level of the classification system includes all cars. The next highest level groups cars on the basis of size. Then, within each of the size categories, cars are grouped according to first one and then another trait. Higher taxa (for example, compact cars) include many different cars. Lower taxa (for example, compact cars that are blue and have two doors and cloth seats) contain far fewer cars. The cars in lower taxa are also much more similar to one another.

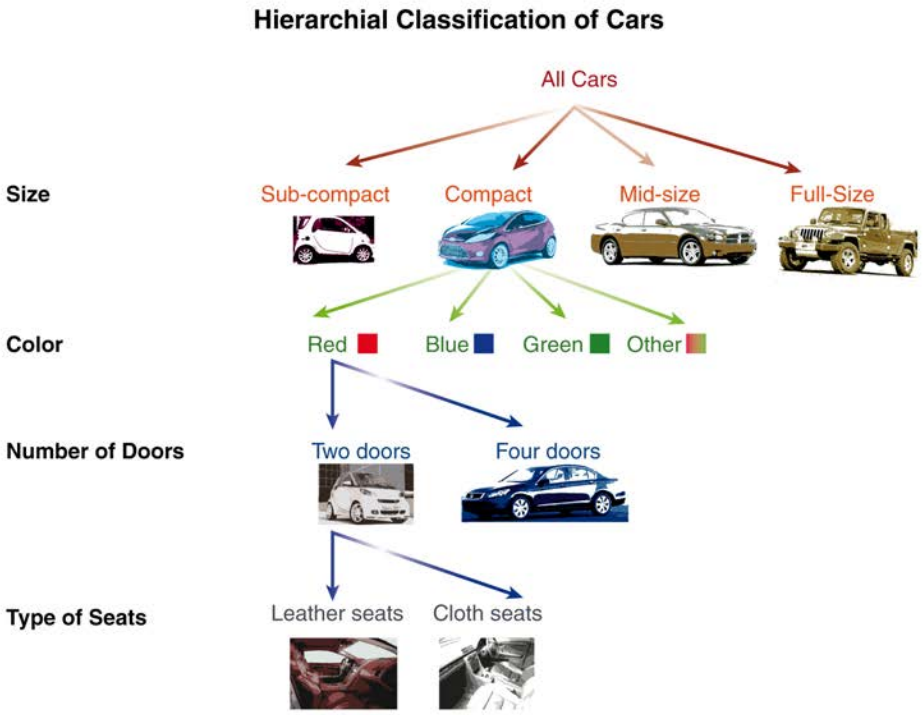

Figure 14.1: Cars can be classified, or grouped, on the basis of various traits. In this classification, the most inclusive groups are the size categories, such as all compact cars or all mid-size cars. The most exclusive groups in this classification share several additional traits, including color, number of doors, and type of seats. Note that just one group for each trait is further divided as an example.

Why do biologists classify organisms? The major reason is to make sense of the incredible diversity of life on Earth. Scientists have identified millions of different species of organisms. Among animals, the most diverse group of organisms is the insects. More than one million different species of insects have already been described. An estimated nine million insect

species have yet to be identified. A tiny fraction of insect species is shown in the beetle collection in **Figure** 14.2.

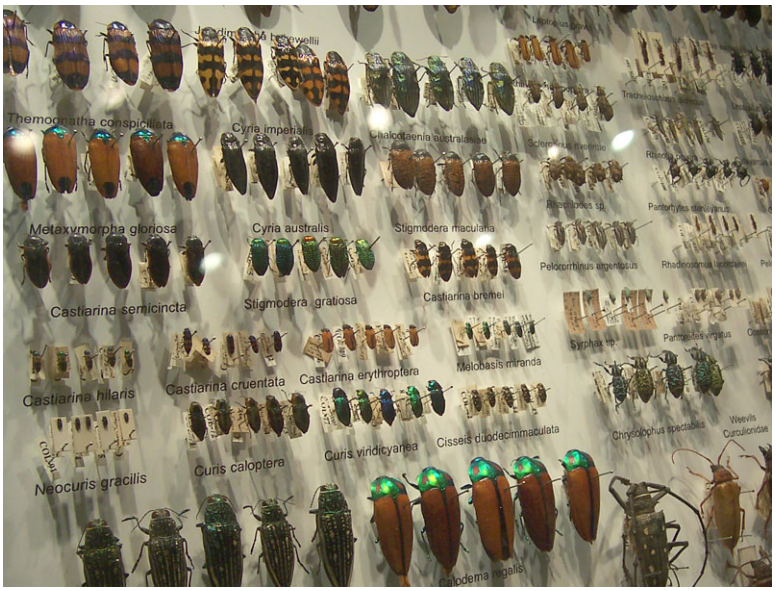

Figure 14.2: Only a few of the more than one million known species of insects are represented in this beetle collection. Beetles are a major subgroup of insects. They make up about 40 percent of all insect species and about 25 percent of all known species of organisms.

As diverse as insects are, there may be even more species of bacteria, another major group of organisms. Clearly, there is a need to organize the tremendous diversity of life. Classification allows scientists to organize and better understand the basic similarities and differences among organisms. This knowledge is necessary to understand the present diversity and the past evolutionary history of life on Earth.

Early Classification Systems

One of the first known systems for classifying organisms was developed by Aristotle. Aristotle was a Greek philosopher who lived more than 2,000 years ago. He created a classification system called the "Great Chain of Being" (See **Figure** 14.3). Aristotle arranged organisms in levels based on how complex, or "advanced," he believed them to be. There were a total of eleven different levels in his system. At the lower levels, he placed organisms that he believed were less complex, such as plants. At higher levels, he placed organisms that he believed were more complex. Aristotle considered humans to be the most complex organisms in the natural world. Therefore, he placed them near the top of his great chain, just below angels and other supernatural beings.

Aristotle also introduced two very important concepts that are still used in taxonomy today:

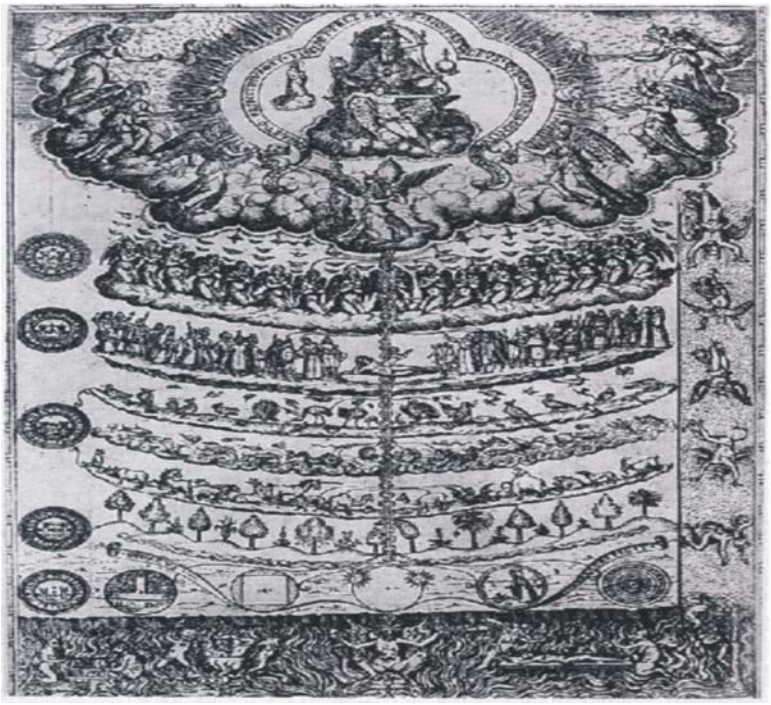

Figure 14.3: The Great Chain of Being was Aristotle's way of classifying organisms. The basis of Aristotle's classification was the presumed complexity of organisms. On that basis, Aristotle placed plants near the bottom of the classification and humans near the top.

genus and species. Aristotle used these two concepts in ways that are similar to, but not as precise as, their current meanings. He used the term *species* to refer to a particular type of organism. He thought each species was unique and unchanging. He used the term **genus** (plural, genera) to refer to a more general grouping of organisms that share certain traits. For example, he grouped together in the same genera animal species with similar reproductive structures.

As early naturalists learned more about the diversity of organisms, they developed different systems for classifying them. All these early classification systems, like Aristotle's, were based on obvious physical traits of form or function. For example, in one classification system, animals were grouped together on the basis of similarities in movement. In this system, bats and birds were grouped together as flying animals, and fishes and whales were grouped together as swimming animals.

Linnaean System of Classification

The most influential early classification system was developed by Carolus Linnaeus. In fact, all modern classification systems have their roots in Linnaeus' system. **Linnaeus** was a Swedish botanist who lived during the 1700s. He is known as the "father of taxonomy." Linnaeus tried to describe and classify the entire known natural world. In 1735, he published his classification system in a work called *Systema Naturae* ("System of Nature").

Linnaean taxonomy divides all of nature into three kingdoms: animal, vegetable (or plant), and mineral. (The mineral kingdom does not include living organisms, so it is not discussed further here.) Both plant and animal kingdoms are subdivided into smaller and smaller categories of organisms. An updated version of Linnaean taxonomy is shown in **Figure** 14.4.

Linnaean Classification System (Revised)

The classification in **Figure** 14.4 includes a few more taxa than Linnaeus identified. However, it follows the same general plan as Linnaeus' original taxonomy. The taxa are below:

- **Kingdom**—This is the highest taxon in Linnaean taxonomy, representing major divisions of organisms. Kingdoms of organisms include the plant and animal kingdoms.
- **Phylum** (plural, phyla)—This taxon is a division of a kingdom. Phyla in the animal kingdom include chordates (animals with an internal skeleton) and arthropods (animals with an external skeleton).
- **Class**—This taxon is a division of a phylum. Classes in the chordate phylum include mammals and birds.
- **Order**—This taxon is a division of a class. Orders in the mammal class include rodents and primates.
- **Family**—This taxon is a division of an order. Families in the primate order include hominids (apes and humans) and hylobatids (gibbons).

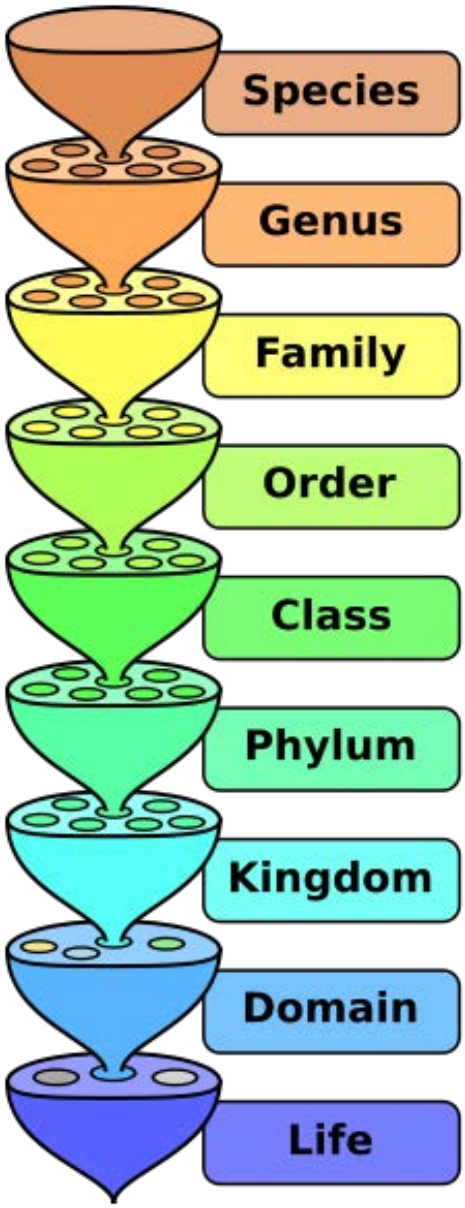

Figure 14.4: This is an updated version of Linnaeus' original classification system. In this classification system, organisms are classified into a hierarchy of taxa. First, all organisms are divided into kingdoms. Further subdivisions place organisms in smaller, more exclusive taxa, all the way down to the level of the species.

- **Genus**—This taxon is a division of a family. Genera in the hominid family include *Homo* (humans) and *Pan* (chimpanzees).
- **Species**—This taxon is below the genus and the lowest taxon in Linnaeus' system. Species in the *Pan* genus include *Pan troglodytes* (common chimpanzees) and *Pan paniscus* (pygmy chimpanzees).

To remember the order of the taxa in Linnaean taxonomy, it may help to learn a mneumonic, a sentence to help remember a list, in which the words begin with the same letters as the taxa: k, p, c, o, f, g, and s. One sentence you could use is: **King Philip came over for green sugar.** Can you think of others?

Table 14.1 shows the classification of the human species. The table also lists some of the physical traits that are the basis of the classification. For example, humans are members of the animal kingdom. Animals are organisms capable of independent movement. Within the animal kingdom, humans belong to the mammal class. Mammals are animals that have fur or hair and milk glands. At each lower taxon, additional physical traits further narrow the group to which humans belong. The final grouping, the species *sapiens* (as in *Homo sapiens*), includes only organisms that have all of the traits listed in the table.

Table 14.1: **Classification of the Human Species**

Taxon	Name	Traits[1]
Kingdom	Animal	Organisms capable of moving on their own.
Phylum	Chordate	Animals with a notochord (flexible rod that supports the body).
Class	Mammal	Chordates with fur or hair and milk glands.
Order	Primate	Mammals with collar bones, grasping hands with fingers.
Family	Hominid	Primates with three-dimensional vision, relatively flat face.
Genus	*Homo*	Hominids with upright posture, large brain.
Species	*sapiens*	Members of the genus *Homo* with a high forehead, thin skull bones.

[1] Only one or two traits per taxon are listed in the table as examples. Additional traits may be needed to properly classify species. (*Source :* http://en.wikipedia.org/wiki/Linnaean_taxonomy)

Although Linnaeus grouped organisms according to their physical similarities, he made no claims about relationships between similar species. Linnaeus lived a century before Charles Darwin, so the theory of evolution had not yet been developed. Darwin explained how evolution, or changes in species over time, can explain the diversity of organisms (see the *Evolutionary Theory* chapter). In contrast, Linnaeus (like Aristotle before him) thought of each species as an unchanging "ideal type." Individual organisms that differed from the species' ideal type were considered deviant and imperfect.

Binomial Nomenclature

The single greatest contribution that Linnaeus made to science is his method of naming species. This method, called **binomial nomenclature,** gives each species a unique, two-word name (also called a scientific or Latin name). Just like we have a first and last name, organisms have a distinguishable two word name as well. The two words in the name are the genus name and the species name. For example, the human species is uniquely identified by its genus and species names as *Homo sapiens.* No other species has this name.

Both words in a scientific name are Latin words or words that have been given Latin endings. The genus name is always written first and starts with an upper-case letter. The species name is always written second and starts with a lower-case letter. Both names are written in italics.

As another example, consider the group of organisms called *Panthera.* This is a genus in the cat family. It consists of all large cats that are able to roar. Within the genus *Panthera,* there are four different species that differ from one another in several ways. One obvious way they differ is in the markings on their fur as shown in **Figure** 14.5, *Panthera leo* (lion species) has solid-colored fur, *Panthera tigris* (tiger species) has striped fur, and the other two *Panthera* species have fur with different types of spots. As this example shows, the genus name *Panthera* narrows a given cat's classification to big cats that roar. Adding the species name limits it to a single species of cat within this genus.

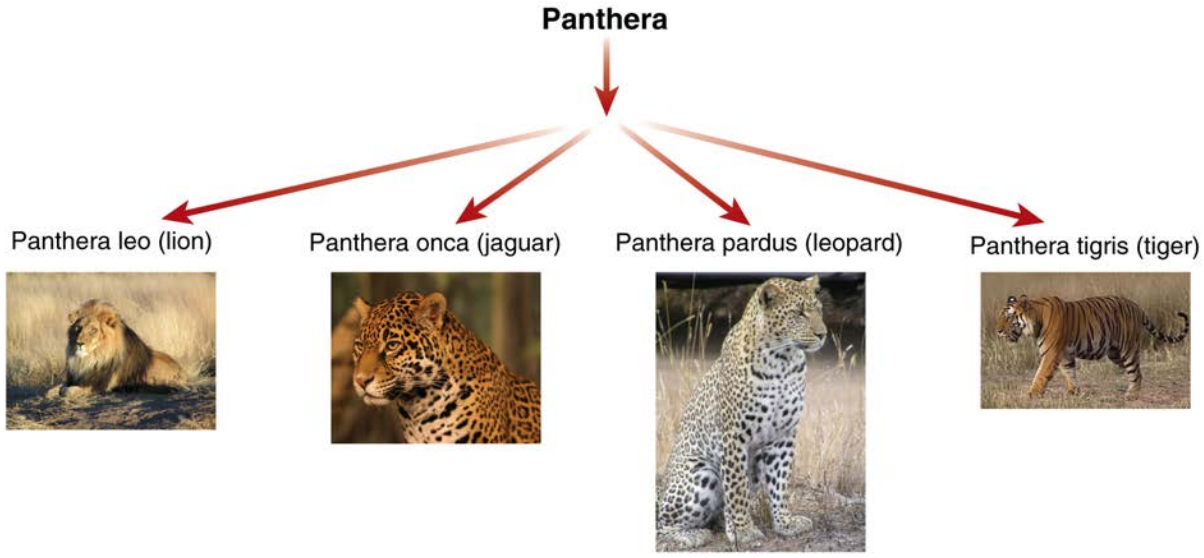

Figure 14.5: . All four species in the Panthera genus are similar, but each is a unique type of organism, clearly identified by its combined genus and species name.

Why is Linnaeus' method of naming organisms so important? Before Linnaeus introduced his method, naming practices were not standardized. Some names were used to refer to more than one species. Conversely, the same species often had more than one name. In addition, a name could be very long, consisting of a string of descriptive words. For example, at one time, common wild roses were named *Rosa sylvestris alba cum rubore folio glabro.* Names such as this were obviously cumbersome to use and hard to remember.

For all these reasons, there was seldom a simple, fixed name by which a species could always be identified. This led to a great deal of confusion and misunderstanding, especially as more and more species were discovered. Linnaeus changed all that by giving each species a unique and unchanging two-word name. Linnaeus's method of naming organisms was soon widely accepted and is still used today.

Changes in the Linnaean System

Linnaean taxonomy has been revised considerably since it was introduced in 1735. One reason revisions have been needed is that many new organisms have been discovered since Linnaeus' time. Another reason is that scientists started classifying organisms on the basis of evolutionary relationships rather than solely on the basis of similarities in physical traits.

Scientists have had to add several new taxa to the original Linnaean taxonomy in order to accommodate new knowledge of organisms and their evolutionary relationships. Examples of added taxa include the **subphylum**, **superfamily**, and **domain**.

- A subphylum is a division of a phylum that is higher than the class. An example of a subphylum is Vertebrates (animals with a backbone). It is a subphylum of the Chordate phylum (animals with a notochord).
- A superfamily is a taxon that groups together related families but is lower than the order. An example of a superfamily is Hominoids (apes). This superfamily consists of the Hominid family (gorillas, chimps, and humans) and the Hylobatid family (gibbons). **Figure** 14.6 shows species from both of these families of the Hominoid superfamily.
- A domain is a taxon higher than the kingdom. An example of a domain is Eukarya, which includes both plant and animal kingdoms. You can read more about domains in Lesson 14.3.

Figure 14.6: The Hominoid superfamily includes the Hominid and Hylobatid families. Members of the Hominid family are chimpanzees (, left), gorillas, orangutans, and humans. Members of the Hylobatid are all gibbons (, right).

Lesson Summary

- Taxonomy is the scientific classification of organisms. Scientists classify organisms in order to make sense of the tremendous diversity of life on Earth.
- Linnaean taxonomy groups organisms in a hierarchy of taxa, based on similarities in physical traits. Linnaeus' binomial nomenclature gives each species a unique two-word name.

Review Questions

1. Define taxonomy.
2. What contributions did Carolus Linnaeus make to taxonomy?
3. List the order of taxa in Linnaean taxonomy, from most to least inclusive.
4. What is binomial nomenclature?
5. Create a hierarchical taxonomy to classify writing implements, such as pens and pencils. Use a diagram to show your taxonomy.
6. Assume that a new organism has been discovered. It has a notochord, fur, forward-facing eyes, and grasping hands with fingers. In which taxa should the new organism be placed? Justify your answer.
7. Explain why biologists need to classify organisms.
8. Why was Linnaeus' naming system such an important contribution to biology?

Further Reading / Supplemental Links

- Wilfrid Blunt, *Linnaeus: The Compleat Naturalist.* Princeton University Press, 2002.
- Paul Lawrence Farber, *Finding Order in Nature.* Johns Hopkins University Press, 2000.
- Judith Winston, *Describing Species.* Columbia University Press, 1999.

Vocabulary

binomial nomenclature Linnaeus' method of naming species using a unique two-word name made up of the genus and species names.

class Taxon that is a division of a phylum.

family Taxon that is a division of an order.

genus Taxon that is a division of a family.

kingdom Major grouping of organisms, such as plants or animals.

Linnaeus Swedish botanist who lived during the 1700s and is known as the "father of taxonomy."

order Taxon that is a division of a class.

phylum Taxon that is a division of a kingdom.

species Group of organisms that are similar enough to mate and produce offspring together.

taxa Categories of organisms in a taxonomy.

taxonomy Method of organizing living things into groups.

Points to Consider

Linnaeus grouped together organisms on the basis of similarities in physical traits.

- Can you think of other similarities that could be used to group organisms?
- What other types of traits might related organisms share?
- What about similarities in molecules, such as DNA, among related organisms?

14.2 Lesson 14.2: Phylogenetic Classification

Lesson Objectives

- Understand the concept of phylogenetic classification.
- Outline how cladistics generates cladograms and identifies clades.
- Compare phylogenetic and Linnaean classification systems.
- Explain how nucleic acid base sequences are used in phylogenetic classification.

Introduction

In the century after Linnaeus published his system of classification, ideas about classifying organisms began to change. In 1859, Darwin published his major work on evolution, *On the Origin of Species by Natural Selection.* After that, there was more and more interest in classifying organisms, incorporating the evolutionary history, including the genetic relationships, of the organisms.

Phylogeny

The evolutionary history of a group of genetically related organisms is called a **phylogeny**. It includes ancestor species and descendant species. A phylogeny is usually represented by a tree diagram called a **phylogenetic tree**. An early example of a phylogenetic tree is Darwin's "Tree of Life" (see **Figure** 14.7). In this diagram, Darwin was trying to show how he thought evolution had occurred. The tree shows how species evolved through time, from the bottom of the tree to the top. As species evolved, they formed new branches on the tree of life. Some of these species eventually branched into additional descendant species. Others died out, or went extinct, without leaving any descendants.

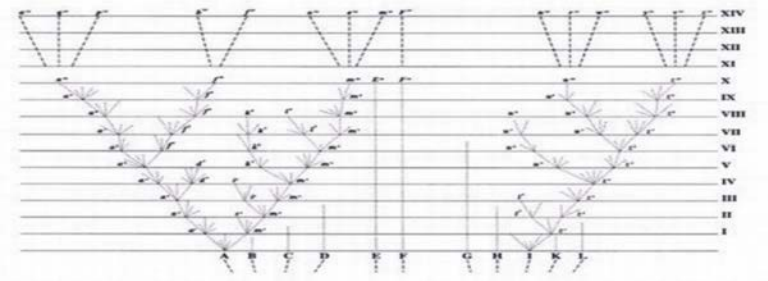

Figure 14.7: . This branching diagram represents the evolutionary histories of different species. It is the only diagram that originally appeared in Darwin's famous 1859 book,

Modern biologists still use phylogenetic trees to represent evolutionary histories. A simple phylogenetic tree is shown in **Figure** 14.8. The tips of the branches represent genetically related species. The branching points represent common ancestors. A **common ancestor** is the last ancestor species that two descendant species shared before they took different evolutionary paths. In the tree in **Figure** 14.8, species 1 and 2 shared a more recent common ancestor with each other than with species 3. Therefore, species 1 and 2 are more closely related to one another than to species 3.

Ancestor species are like your own ancestors. Your most recent common ancestor with any siblings you may have is a shared parent. Your most recent common ancestor with a first cousin is a shared grandparent. Your most recent common ancestor with a second cousin is a shared great-grandparent. In general, the more distant the relationship between you and relatives in your own generation, the farther in the past you shared a common ancestor. The same holds true for related species. The more distant the relationship between two related species, the farther back in time they shared a common ancestor.

The most common method of incorporating information into phylogenetic trees is called **cladistics**. Cladistics depicts hypotheses about how organisms are related, based on traits of ancestor and descendent species. Cladistics was developed in the 1950s by a scientist named Willi Hennig. Over the next several decades, it became very popular, and is still widely used today.

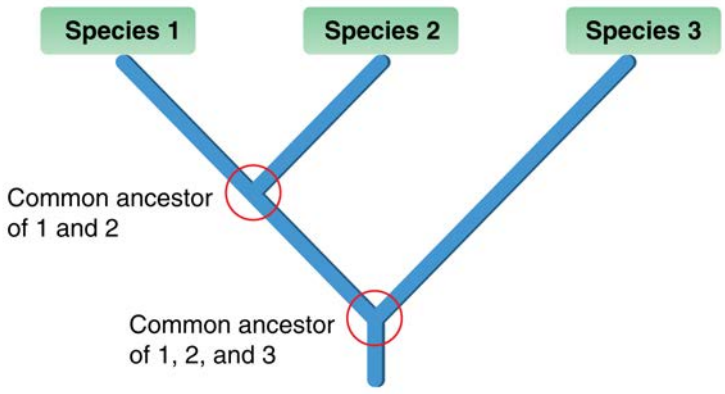

Figure 14.8: . This phylogenetic tree shows how hypothetical species 1, 2, and 3 are related to one another through common ancestors.

The term *cladistics* comes from the word *clade*. A **clade** is a group of organisms that includes an ancestor species and all of its descendants. A diagram showing evolutionary relationships within one or more clades is called a **cladogram**. A clade is a relative concept. How you define a clade depends on which species you are interested in classifying. Small clades can includes as few as two species and their common ancestor. The larger clades can include many more species and their common ancestors.

As another example, consider the cladogram of insect phylogeny shown in **Figure** 14.9. According to this cladogram, beetles first branched off from their common ancestor with other insects. Then, the group that includes wasps, bees, and ants branched off. Finally, flies branched off from their common ancestor with butterflies and moths. All insects can be considered a clade because they have a common ancestor. Butterflies, moths, and flies can also be considered a clade for the same reason. Can you identify other clades in **Figure** 14.9? For example, can you find the clade of all nonbeetle insects?

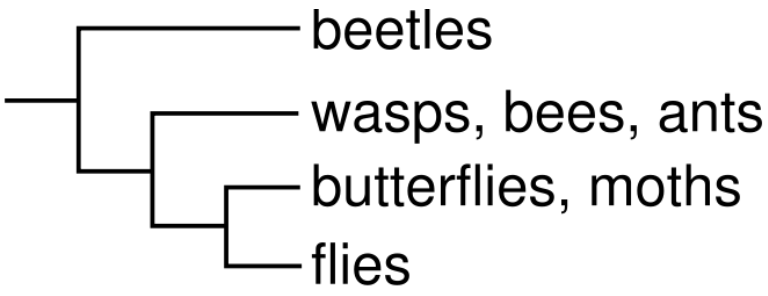

Figure 14.9: Cladogram of Insect Phylogeny. Based on this cladogram, flies shared a more recent common ancestor with butterflies and moths than either group shared with other insects. What other evolutionary relationships does the cladogram reveal?

Generating Cladograms

How do scientists construct cladograms like the one in **Figure** 14.10? The starting point is a set of data on traits of a group of related species. The traits could be physical traits, genetic traits, or both (see **Evidence for Evolutionary Relationships** below). The next step is deciding which traits were inherited from the common ancestor and which traits evolved only in a descendant species after splitting off from the common ancestor. Traits inherited from a common ancestor are called **ancestral traits**. Traits that evolved since two groups shared a common ancestor are called **derived traits** and both types of traits are illustrated in **Figure** 14.10.

Ancestral and Derived Traits in Cladistic Analysis

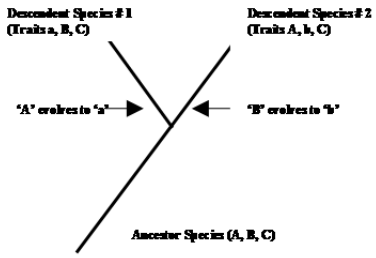

Figure 14.10: In this cladogram, the ancestor species has traits A, B, and C, so these are ancestral traits. During the process of evolution, trait A evolves to trait a and trait B evolves to trait b. These new traits (a and b) are derived traits. Organisms can be classified into separate groups (species #1 or species #2) on the basis of these derived traits.

Consider birds as an example. A derived trait in birds is feathers. The trait is present only in birds and was not inherited from a common ancestor of birds and other organisms. An example of an ancestral trait in birds is the presence of eyes. Eyes are present not only in birds but also in many other groups of animals that share a common ancestor with birds. Therefore, the presence of feathers can identify an organism as a bird, but the presence of eyes cannot. In cladistics, the sharing of derived traits is the most important evidence for evolutionary relationships. Organisms with the same derived traits (such as feathers) are grouped in the same clade.

A derived trait is not necessarily an entirely new trait. More often it

is a modified form of an ancestral trait. For example, birds evolved feathers from the scales that were already present in their reptile ancestor. Similarly, mammals evolved fur from the scales of their reptile ancestor.

More than one possible cladogram usually can be created from the same set of data. In fact, the number of possible cladograms increases exponentially with the number of species included in the analysis. Only one cladogram is possible with two species. More than 100 cladograms are possible with five species. With nine species, more than two million cladograms are possible! **Figure** 14.11 shows just six of the many possible cladograms that can be generated for five species.

Six Possible Cladograms for Five Hypothetical Species

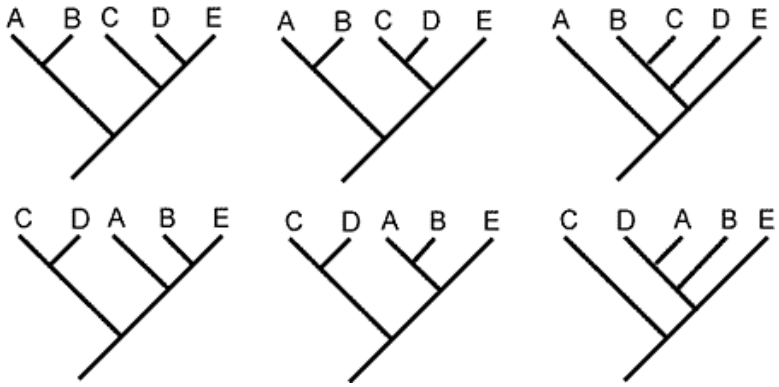

Figure 14.11: The same set of data on five related species may generate over 100 possible cladograms. Just six are shown here. In cladogram 1 (top, left), D and E share a more recent common ancestor than either shares with C. In cladogram 2 (top, middle), C and D share a more recent common ancestor than either shares with E. Compare how each of the remaining cladograms differs from the others.

How do scientists know which of many possible cladograms is the "right" one? There is no right or wrong cladogram. However, some cladograms fit the facts better than others. Statistical methods can be used to determine which cladogram best fits a particular data set. An important deciding factor is parsimony. **Parsimony** means choosing the simplest explanation from among all possible explanations. In cladistics, parsimony usually means choosing the cladogram with the fewest branching points.

A cladogram shows just one of many possible phylogenies for a group of organisms. It can provide insights about how evolution occurred. However, a cladogram should not be considered a model of actual evolutionary events. It does not necessarily show what really happened. It just shows what could have happened.

Phylogenetic Classification

A cladogram shows how species may be related by descent from a common ancestor. A classification of organisms on the basis of such relationships is called a **phylogenetic classification**. A phylogenetic classification involves placing organisms in a clade with their common ancestor. Consider the cladogram in **Figure** 14.12. It groups birds in the same clade as reptiles, because a variety of evidence suggests that birds evolved from a reptile ancestor. The cladogram places mammals in a separate clade, because evidence suggests that mammals evolved from a different ancestor.

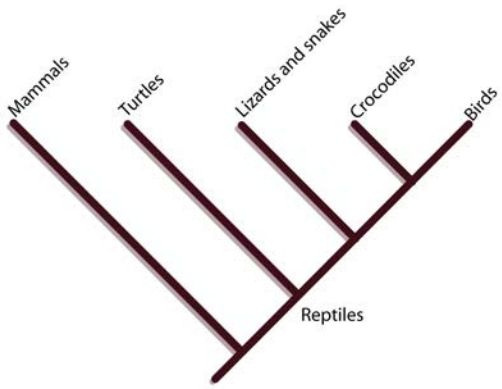

Figure 14.12: . This cladogram represents the evolutionary history of reptiles, birds, and mammals. The reptile clade includes birds. Mammals are in a separate clade.

Figure 14.13 shows the phylogenetic classification of reptiles, birds, and mammals based on the cladogram in **Figure** 14.12. Birds are grouped with reptiles in one clade, called the Sauropsids. Mammals and their reptile-like ancestor are grouped in a separate clade, called the Synapsids. Compare this phylogenetic classification with the Linnaean classification, also shown in **Figure** 14.13. In the Linnaean classification, reptiles, birds, and mammals are all placed in separate classes based on differences in physical traits. This classification artificially separates both birds and mammals from their reptilian ancestors. It also illustrates the difficulty of showing evolutionary relationships with Linnaean taxonomy.

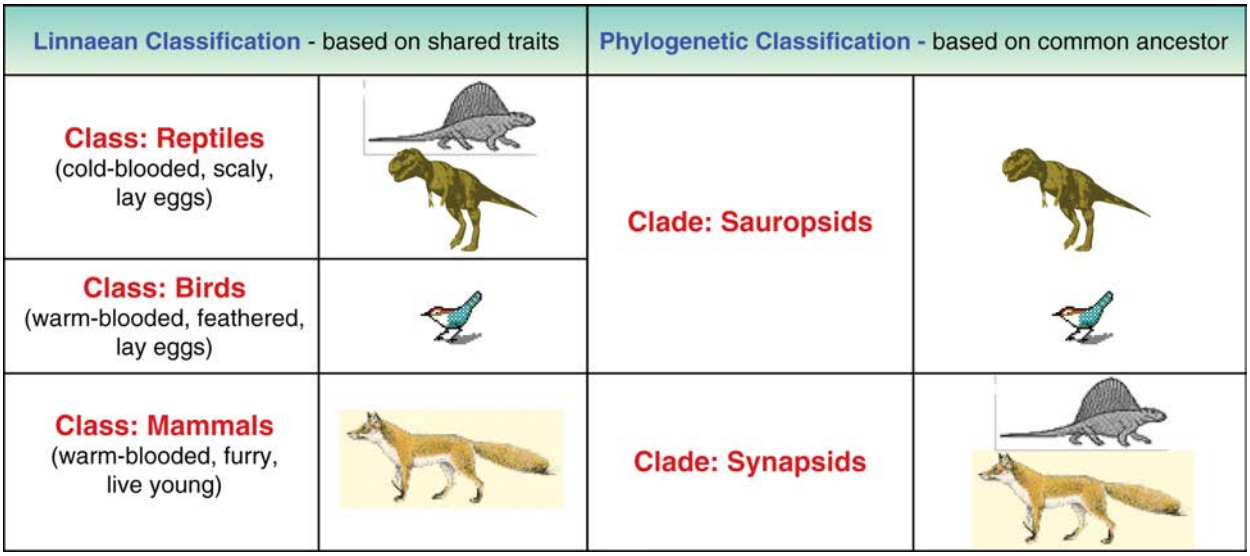

Figure 14.13: The cladistic classification on the right assumes that mammals and birds evolved from different reptile ancestors. Mammals are placed in one clade, and birds are placed in another clade (with modern reptiles). Compare this classification with the Linnaean classification on the left. Why are birds and reptiles placed in separate classes in the Linnean taxonomy

Phylogenetic and Linnaean Classifications of Reptiles, Birds, and Mammals

Both phylogenetic and Linnaean classification systems have advantages and drawbacks (see the point by point comparison in the two lists, below). As an overall approach, most biologists think that phylogenetic classification is preferable to Linnaean classification. This is because it is based on evolutionary relationships and not just similarities in physical traits that may or may not have evolutionary significance. However, both approaches have a place in the classification of organisms. Linnaean binomial names are still needed to identify species, because phylogenetics does not include a method for naming species. In addition, many higher taxa in the Linnaean system, such as birds and mammals, remain useful in phylogenetic classifications. This is because they are also clades.

Phylogenetic Classification

1. Treats all levels of a cladogram as equivalent.
2. Places no limit on the number of levels in a ladogram.
3. Primary goal is to show the process of evolution.
4. It is limited to organisms that are related by ancestry.
5. Does not include a method for naming species.

Linnaean Classification

1. Treats each taxa uniquely and has a special name or each (e.g., genus, species).
2. Has fixed numbers and types of taxa.
3. Primary goal is to group species based on similarities in physical traits.
4. Can include any organisms without regard to ancestry.
5. Has a method for giving unique names to species.

Phenetics is an older method to classify organisms. Phenetics is based on overall similarity, usually in morphology or other observable traits, regardless of their evolutionary relation. Phenetics has largely been replaced by cladistics for research into evolutionary relationships among species. Phenetic techniques include various forms of clustering and ordination of traits. These are sophisticated ways of reducing the variation displayed by organisms to a manageable level. Phenetic analyses do not distinguish between traits that are inherited from an ancestor and traits that evolved anew in one or several lineages. Consequently, phenetic analyses can be misled by convergent evolution and adaptive radiation.

Evidence for Evolutionary Relationships

Traditionally, evidence for evolutionary relationships included similarities in physical traits of form or function. For example, in Linnaean taxonomy, homeothermy (warm-bloodedness) is one of the traits used to separate both birds and mammals from other animals (see **Figure** 14.13). However, this trait is not suitable for showing evolutionary relationships between birds and mammals. This is because birds and mammals did not inherit the trait of homeothermy from a common ancestor. Both groups independently evolved the trait. The presence of homeothermy in both birds and mammals is an example of convergent evolution (see the *History of Life* chapter). In general, convergent evolution may make two groups seem to be more closely related than they really are. Using such traits for phylogenetic analysis can lead to misleading phylogenetic classifications.

Similarities among nucleic acid base sequences provide some of the most direct evidence of evolutionary relationships (see the *Evolutionary Theory* chapter). Nucleic acids directly control genetic traits and copies of nucleic acids are actually passed from parents to offspring. Therefore, similarities in these traits are likely to reflect shared ancestry. By the 1960s, scientists had found ways to sequence the bases in nucleic acids. This coincided with the growing popularity of cladistics. In cladistic analysis, similar nucleic acid base sequences are assumed to indicate descent from a common ancestor. The more similar the sequences, the more recently two groups are assumed to have shared a common ancestor.

Many base sequence comparisons have confirmed genetic relationships that were assumed on

the basis of similarities in physical traits. For example, 96 percent of the DNA in humans and chimpanzees is the same. This agrees, in general, with the Linnaean classification of chimpanzees as close human relatives (see Lesson 14.1).

Most biologists interested in taxonomy now use nucleic acid sequences or other related molecular data to classify organisms. However, using nucleic acid base sequences for phylogenetic analysis is not without its drawbacks. Two of the drawbacks are:

- Data on nucleic acids can rarely be obtained for extinct species. This is true even for species represented by fossils. Fossil DNA and RNA generally are not sufficient in quantity or quality to be useful for such analyses.
- Base sequence data may be influenced by horizontal gene transfer. This occurs when an organism passes DNA to an unrelated organism. First discovered in bacteria in 1959, it is now known to be common in bacteria and some other microorganisms. Horizontal gene transfer can make species seem more closely related than they really are.

Because of horizontal gene transfer, some biologists have started to question whether phylogenetic trees are the best way to show evolutionary relationships. This is especially true for those biologists that are interested in classifying bacteria. An entirely new process of determining evolutionary relationships may be needed in order to include horizontal gene transfer.

Lesson Summary

- Phylogeny is the evolutionary history of a group of genetically related organisms. It is usually represented by a diagram called a phylogenetic tree.
- Cladistics is the most widely used method of generating phylogenetic trees. It is based on evolutionary ancestry and generates trees called cladograms. Cladistics also identifies clades, which are groups of organisms that include an ancestor species and its descendants.
- Classifying organisms on the basis of descent from a common ancestor is called phylogenetic classification. Phylogenetic classification may or may not agree with Linnaean taxonomy, which is based on similarities in physical traits regardless of ancestry.
- The most direct evidence for evolutionary relationships is similarity in base sequences of the nucleic acids DNA and RNA. The more similar the base sequences of two species, the more closely related the species are assumed to be.

Review Questions

1. What is a phylogeny?
2. Define cladistics.

3. What does phylogenetic classification involve?
4. Why are nucleic acid base sequences directly related to evolution?
5. In cladogram 6 of **Figure** 14.11, explain how the five species are related to one.
6. Identify an ancestral trait and a derived trait in mammals. Explain your answer.
7. Explain why a cladogram represents only one hypothesis about how evolution occurred.
8. Compare the advantages of Linnaean and phylogenetic classification systems.

Further Reading / Supplemental Links

- http://evolution.berkeley.edu/evolibrary/article/0_0_0/phylogenetics_01
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- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/T/Taxonomy.html
- http://www.genome.gov/12514316
- http://www.palaeos.com/Systematics/Cladistics/incompatable.html

Vocabulary

ancestral traits Traits inherited from a common ancestor.

clade Group of organisms that includes an ancestor species and all of its descendants.

cladistics Method of making evolutionary trees based on comparisons of traits of ancestor and descendant species.

cladogram Diagram showing evolutionary relationships within one or more clades.

common ancestor Last ancestral species that two descendant species shared before they took different evolutionary paths.

derived traits Traits that evolved since two groups shared a common ancestor.

parsimony Choosing the simplest explanation from among all possible explanations.

phylogenetic classification Classification of organisms on the basis of evolutionary relationships.

phylogenetic tree Diagram representing a phylogeny.

phylogeny Evolutionary history of a group of genetically related organisms.

Points to Consider

When Linnaeus developed his classification system in the early 1700s, he knew almost nothing about microorganisms (microscopic organisms). Therefore, he did not include microorganisms in his taxonomy.

- How do you think microorganisms should be classified?
- Where do you think microorganisms should be placed in Linnaean taxonomy?
- Do you think a new taxon might be needed for microorganisms?

14.3 Lesson 14.3: Modern Classification Systems

Lesson Objectives

- Identify the four new kingdoms that were added to the original Linnaean taxonomy.
- Describe the three domains of the three-domain system of classification.
- Explain why the three-domain system may need revision in the future.

Introduction

Linnaeus established two kingdoms of organisms in his classification system: Plantae (the plant kingdom) and Animalia (the animal kingdom). Since then, scientists have repeatedly revised the Linnaean system. They have added several new kingdoms and other taxa. These changes were necessary as scientists learned more about life on Earth.

New Kingdoms

Between 1866 and 1977, a total of four new kingdoms were added to the original plant and animal kingdoms identified by Linnaeus. The new kingdoms include Protista (protists), Fungi, Monera (eubacteria), and Archaea (archaebacteria). **Table** 14.2 identifies the scientists who introduced the kingdoms and the dates the kingdoms were introduced. The table starts with the two-kingdom system introduced by Linnaeus in 1735.

Table 14.2: **Kingdoms in the Classification of Organisms**

Number of Kingdoms	Two	Three	Four	Five	Six
Scientist	Linnaeus	Haeckel	Copeland	Whittaker	Woese
Date	1735	1866	1956	1969	1977
Names of Kingdoms	Plantae Animalia	Plantae Animalia Protista	Plantae Animalia Protista Monera	Plantae Animalia Protista Fungi Monera	Plantae Animalia Protista Fungi Monera Archaea

(*Source:* http://en.wikipedia.org/wiki/Kingdom_%28biology%29, *License:* GNU Free Documentation)

The Protist Kingdom

When Linnaeus created his taxonomy, microorganisms were almost unknown. As scientists began studying single-celled organisms under the microscope, they generally classified them as either plants and or animals. For example, bacteria are single-celled organisms, some of which make their own food. They were classified as plants, which also make their own food. Protozoa are single-celled organisms that can move on their own. They were classified as animals, which are organisms that have independent movement.

As more single-celled organisms were identified, many didn't seem to fit in either the plant or the animal kingdom. As a result, scientists could not agree on how to classify them. To address this problem, in 1866, biologist Ernst Haeckel created a third kingdom for all single-celled organisms. He called this kingdom Protista. **Figure** 14.14 shows drawings that Haeckel made of several different types of **protists** as they looked under a microscope. The drawings show some of the diversity of microorganisms.

Figure 14.14: . Biologist Ernst Haeckel made these drawings of various types of single-celled organisms as viewed under a microscope. Based on his extensive knowledge of the diversity of microorganisms, Haeckel introduced a new kingdom just for single-celled life forms, called the protist kingdom. This was the first major change in the original Linnaean taxonomy.

The Bacteria Kingdom

Haeckel's protist kingdom represented all known single-celled organisms, including both bacteria and protozoa. In the early 1900s, scientists discovered that bacterial cells are very different not only from plant and animal cells but also from the cells of protists, such as protozoa. **Figure** 14.15 shows a bacterial cell, a protozoan cell, and an animal cell. When you compare the three cells, what differences do you see? The major difference is that, unlike the protozoan and animal cells, the bacterial cell does not contain a nucleus surrounded by a nuclear membrane. Instead, its DNA is found in the cytoplasm of the cell. Organelles in the bacterial cell also lack surrounding membranes.

In the 1920s, microbiologist Edouard Chatton gave bacteria the name prokaryotes. He defined **prokaryote** as an organism whose cells lack nuclei. He gave the name eukaryotes to all other organisms. He defined **eukaryote** as an organism whose cells have nuclei (see the *Cell Structure and Function* chapter). Chatton proposed placing prokaryotes and eukaryotes in a new taxon above the kingdom, called the superkingdom. However, this idea did not catch on, and most biologists continued to place bacteria in the protist kingdom.

Over the next several decades, scientists learned more about the tremendous number and diversity of bacteria. They started to see a need for a separate bacteria kingdom. By 1956, biologist Herbert Copeland proposed placing bacteria in a new kingdom called Monera. With

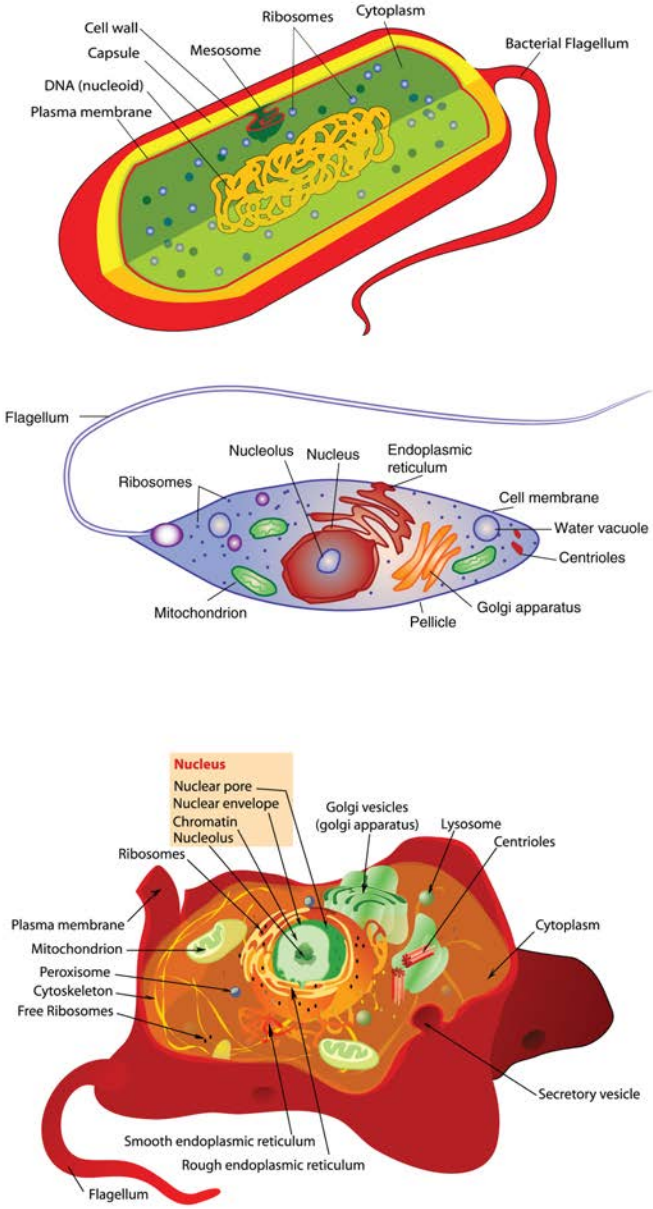

Figure 14.15: . Prokaryote and eukaryote cells differ significantly in their structure. Unlike prokaryote cells (upper figure), eukaryote cells (middle figure, protist cell; lower figure, animal cell) have a nucleus, which is separated by membranes from the cytoplasm of the cell. Their organelles also have membranes. Herbert Copeland thought that these and other differences were significant enough to place prokaryote and eukaryote organisms in different superkingdoms.

the addition of the **Monera** kingdom, Linnaean taxonomy became a four-kingdom system (See **Table** 14.2).

> **Bacteria are the most numerous organisms on Earth. In a single gram of soil, there are typically 40 million bacterial cells. The human body also contains 10 times as many bacterial cells as human cells. Most of these bacteria are on the skin or in the digestive tract.**

The Fungi Kingdom

In the late 1960s, ecologist Robert Whittaker proposed adding a fifth kingdom to Linnaean taxonomy to represent fungi. **Fungi** are eukaryote organisms such as mushrooms and molds. Up until then, fungi had been classified in the plant kingdom. Whittaker separated fungi from plants on the basis of differences in metabolism. Plants make their own food in the process of photosynthesis, whereas fungi obtain nutrients by breaking down dead organisms (see the *Fungi* chapter). Separating fungi from plants resulted in five kingdoms, which are illustrated in **Figure** 14.16. The five-kingdom system soon became widely accepted.

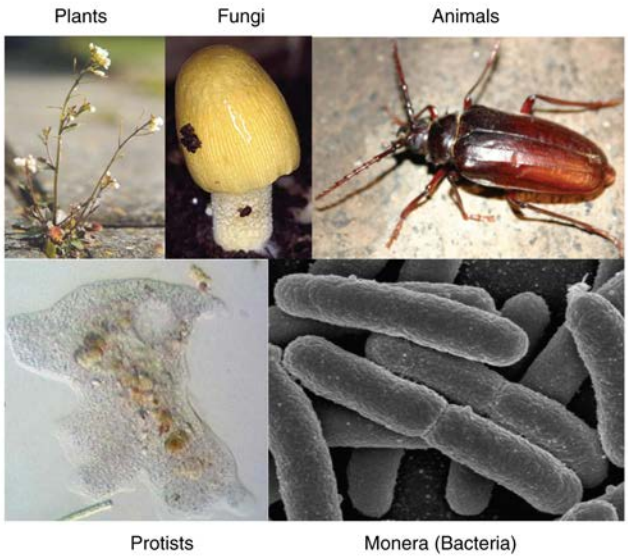

Figure 14.16: This five-kingdom system of classification was proposed by ecologist Robert Whittaker in the late 1960s. Whittaker added the Fungi kingdom to the earlier four-kingdom classification system.

Two Bacterial Kingdoms

By the 1970s, scientists had started to classify organisms in ways that reflected evolutionary relationships. They had also started using nucleic acid base sequences to identify these relationships (see Lesson 14.2). Nucleic acid sequence data are especially useful for studying bacteria. These organisms are so small that they have few physical traits.

Studies have bacterial nucleic acid sequences have yielded some surprising results. For example, in their research on ribosomal RNA base sequences, microbiologist Carl Woese and his colleagues discovered that bacteria actually include two very different groups of organisms. They called the two groups Eubacteria and Archaebacteria. Examples of organisms from each group are shown in **Figure** 14.17. Although the two types of organisms are similar in appearance, their ribosomal RNA sequences are very different. In 1977, Woese and his colleagues suggested that the original bacteria kingdom should be divided into two new kingdoms, called Eubacteria and Archaebacteria. This resulted in a six-kingdom taxonomy that has been widely accepted for many years.

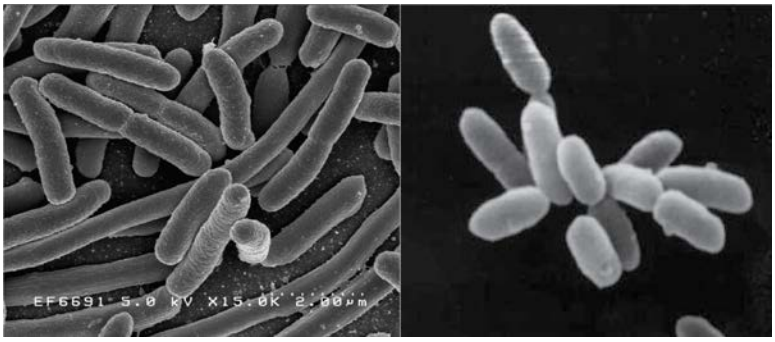

Figure 14.17: Left, Eubacteria (now called Bacteria), Right, Archaebacteria (now called Archaea). Appearances can be deceiving! These two microorganisms are very different from one another, despite their outward similarities. Both organisms used to be classified in the bacteria kingdom. Woese suggested placing them in different kingdoms, called the eubacteria and archaebacteria kingdoms.

Domains

Woese wasn't completely happy with the six-kingdom system. It didn't show that all four eukaryote kingdoms are more closely related to each other than to the two bacteria kingdoms. It also didn't show that the two bacteria kingdoms are as different from each other as they are from the eukaryote kingdoms. To show these similarities and differences, Woese introduced a new taxon called the **domain**. He defined domain as a taxon higher than the kingdom.

The Three-Domain System

In 1990, Woese and his colleagues proposed a new classification system containing three domains: Bacteria, Archaea, and Eukarya. As shown in **Figure** 14.18, the **Bacteria** domain was formerly the Eubacteria kingdom, and the **Archaea** domain was formerly the Archaebacteria kingdom. The **Eukarya** domain includes all four eukaryote kingdoms: plants, animals, protists, and fungi. The three-domain system emphasizes the similarities among eukaryotes and the differences among eukaryotes, bacteria, and archaea. By using domains, Woese was able to show these relationships without replacing the popular six-kingdom system.

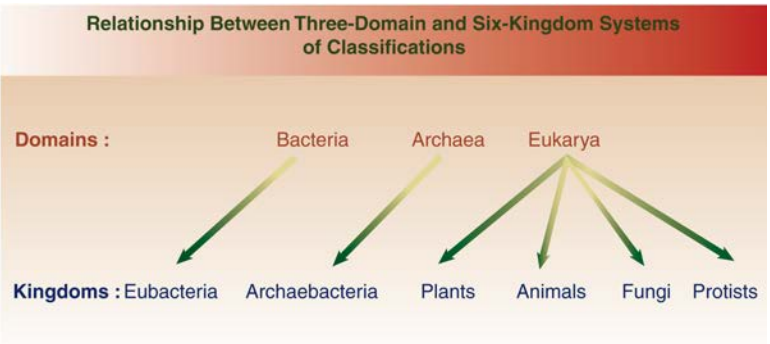

Figure 14.18: This diagram shows how the three-domain system of classification is related to the six-kingdom system. Both Eubacteria and Archaebacteria kingdoms are raised to the level of domains (Bacteria and Archaea domains, respectively) in the three-domain system. The other four kingdoms make up the third domain (Eukarya domain).

Archaea were first found in extreme environments. For example, they were found in the hot water geysers in Yellowstone National park. Archaea have since been found in all of Earth's habitats. They are now known to be present everywhere in high numbers. They may contribute as much as 20 percent to Earth's total biomass.

Woese's three-domain system was quickly adopted by many other biologists. There were some critics, however, who argued that the system put too much emphasis on the uniqueness of Archaea. Later studies confirmed how different Archaea are from other organisms. For example, organisms belogning to Archaea were found to differ from both Eukarya and Bacteria in the composition of their cell membranes and the system they use for DNA replication. These differences convinced most critics that the three-domain system was justified. After its introduction in 1990, the three-domain system became increasingly popular. Within a decade of its introduction, it had largely replaced earlier classifications.

How Are the Three Domains Related?

Comparing ribosomal RNA base sequences, Woese and his colleagues also showed that organisms belonging to Eukarya are more similar to Archaea than they are to Bacteria. **Figure**

14.19 is a phylogenetic tree based on their analysis. This tree places Archaea and Eukarya in the same clade (see Lesson 2). It represents the hypothesis that Archaea and Eukarya shared a more recent common ancestor with each other than with Bacteria.

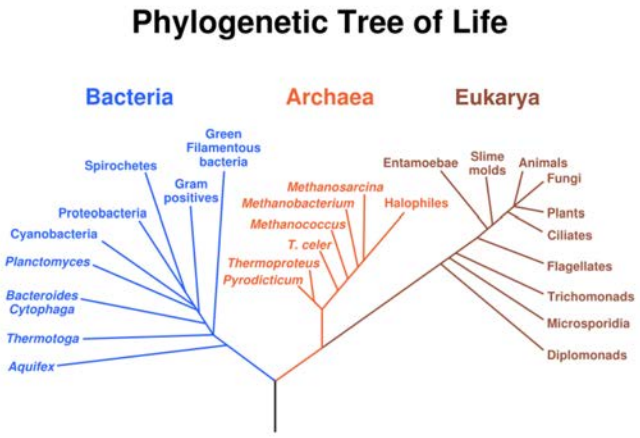

Figure 14.19: This phylogenetic tree is based on comparisons of ribosomal RNA base sequences among living organisms. The tree divides all organisms into three domains: Bacteria, Archaea, and Eukarya. Humans and other animals belong to the Eukarya domain. From this tree, organisms that make up the domain Eukarya appear to have shared a more recent common ancestor with Archaea than Bacteria.

The results of a study published in 2007 seem to conflict with this hypothesis. Comparing DNA base sequences, the 2007 study suggested that the domain Archaea may be older than either Bacteria or Eukarya. That would make Archaea the most ancient group of organisms on Earth. It is not yet known, which, if either, hypothesis is correct. Scientists need to learn more about Archaea and their relationships with other organisms to resolve these questions.

The Future of Classification

The three-domain system is unlikely to be the final word on classification. The system is based on the current state of knowledge. As knowledge increases, the three-domain system may need revision. For example, the number of domains may change as scientists learn more about those life forms we currently know least about.

A recent discovery illustrates this point. In 2003, scientists identified a new virus called mimivirus. It resembles bacteria in size and number of genes. However, the virus cannot respond to stimuli or grow by cell division, both of which are traits of bacteria and other living organisms. Mimivirus' unique combination of traits seems to place it at the boundary between living and nonliving things. Some scientists think mimivirus might represent a new domain of life.

Lesson Summary

- By 1977, four new kingdoms had been added to the plant and animal kingdoms of the original Linnaean taxonomy: Protista, Fungi, Eubacteria, and Archaebacteria.
- In 1990, the three-domain system was introduced and is now the most widely used classification system. The three domains are Bacteria, Archaea, and Eukarya.
- As knowledge of organisms increases in the future, the three-domain system may need revision. For example, new domains may need to be added.

Review Questions

1. Name four new kingdoms that were added to the original Linnaean taxonomy.
2. How do prokaryotes and eukaryotes differ?
3. Why were fungi placed in a separate kingdom from plants?
4. What is a domain?
5. Describe the relationship between the original bacteria kingdom called monera and the domain called bacteria.
6. Explain in which domain you would classify an organism that consists of a single cell with a nucleus.
7. Compare and contrast bacteria, Archaea, and Eukarya.
8. What problem with the six-kingdom classification system was addressed by the three-domain classification system? How did it address the problem?

Further Reading / Supplemental Links

- Olaf Breidbach, *Visions of Nature: The Art and Science of Ernst Haeckel*. Prestel Publishing, 2006.
- John L. Howland, *The Surprising Archaea: Discovering Another Domain of Life*. Oxford University Press, 2000.
- Oladele Ogunseitan, *Microbial Diversity: Form and Function in Prokaryotes*. Wiley-Blackwell, 2004.

Vocabulary

archaea Domain that was formerly the Archaebacteria kingdom.

bacteria Domain that was formerly the Eubacteria kingdom.

domain Taxon higher than the kingdom.

eukarya Domain that includes all four eukaryote kingdoms: plants, animals, protists, and fungi.

eukaryote Organisms whose cells have nuclei.

fungi Kingdom of eukaryote organisms such as mushrooms and molds.

monera Original name of the kingdom that included all bacteria.

prokaryote Organism whose cells lack nuclei.

protista Kingdom of single-celled, eukaryote organisms such as protozoa, often called "protists."

Points to Consider

Robert Whittaker separated the fungi from the plant kingdom on the basis of their different ways of obtaining energy. You might expect Whittaker to focus on this type of difference because he was an ecologist.

- What do you think ecology is?
- What do you think ecologists study?
- In addition to ways of obtaining energy, what traits of organisms do you think ecologists are likely to be most interested in?

Image Sources

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(2) CK-12 Foundation. . CC-BY-SA.

(3) http://en.wikipedia.org/wiki/Image:Phylogenetic-Groups.svg. Public Domain.

(4) http://evolution/berkeley.edu/evolibrary/article/0_0_0/phylogenetics_03. CC-BY-SA.

(5) http://upload.wikimedia.org/wikipedia/en/a/a4/5kingdoms.png. Commons.

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Chapter 15

Principles of Ecology

15.1 Lesson 15.1: The Science of Ecology

Lesson Objectives

- State what ecologists study, and identify levels of organization in ecology.
- Define ecosystem, niche, and habitat, and explain how the concepts are related.
- Describe methods of ecology, such as field studies, sampling, statistical analysis, and modeling.

Introduction

Ecology is the scientific study of the interactions of living things with each other and their relationships with the environment. Ecology is usually considered to be a major branch of biology. However, ecology has a more broad scope, because it includes both organisms and their environments. Examining the interactions between organisms and the environment can provide a basic understanding of the richness of life on earth and can help us understand how to protect that richness, which is increasingly threatened by human activity. Regardless of the challenges associated with conducting research in natural environments, ecologists often carry out field experiments to test their hypotheses.

Organisms and the Environment

Ecology is guided by a number of basic principles. One principle is that each living organism has a continual relationship with every other element in its environment. In this context, the environment includes both living and nonliving components.

Organisms

An **organism** is a life form consisting of one or more cells. All organisms have properties of life, including the ability to grow and reproduce. These properties of life require energy and materials from the environment. Therefore, an organism is not a closed system. Individual organisms depend on and are influenced by the environment.

The Environment

To the ecologist, the **environment** of an organism includes both physical aspects and other organisms. These two components of the environment are called abiotic and biotic components, respectively.

- **Abiotic components**, or abiotic factors, are the non-living physical aspects of the environment. Examples include sunlight, soil, temperature, wind, water, and air.
- **Biotic components**, or biotic factors, are the living organisms in the environment. They include organisms of the same and different species.

Biotic components can be very important environmental influences on organisms. For example, the first photosynthetic life forms on Earth produced oxygen, which led to the development of an oxygen-rich atmosphere (see the *History of Life* Chapter). This change in Earth's atmosphere, in turn, caused the extinction of many life forms for which oxygen was toxic and the evolution of many other life forms for which oxygen was necessary.

Levels of Organization

Ecologists study organisms and their environments at different levels. The most inclusive level is the biosphere. The **biosphere** consists of all the organisms on planet Earth and the areas where they live. It occurs in a very thin layer of the planet, extending from about 11,000 meters below sea level to 15,000 meters above sea level. An image of the biosphere is shown in **Figure** 15.1. Different colors on the map indicate the numbers of food-producing organisms in different parts of the biosphere. Ecological issues that might be investigated at the biosphere level include ocean pollution, air pollution, and global climate change.

Ecologists also study organisms and their environments at the population level. A **population** consists of organisms of the same species that live in the same area and interact with one another. You will read more about populations in the *Populations* chapter. Important ecological issues at the population level include:

- rapid growth of the human population, which has led to overpopulation and environmental damage;

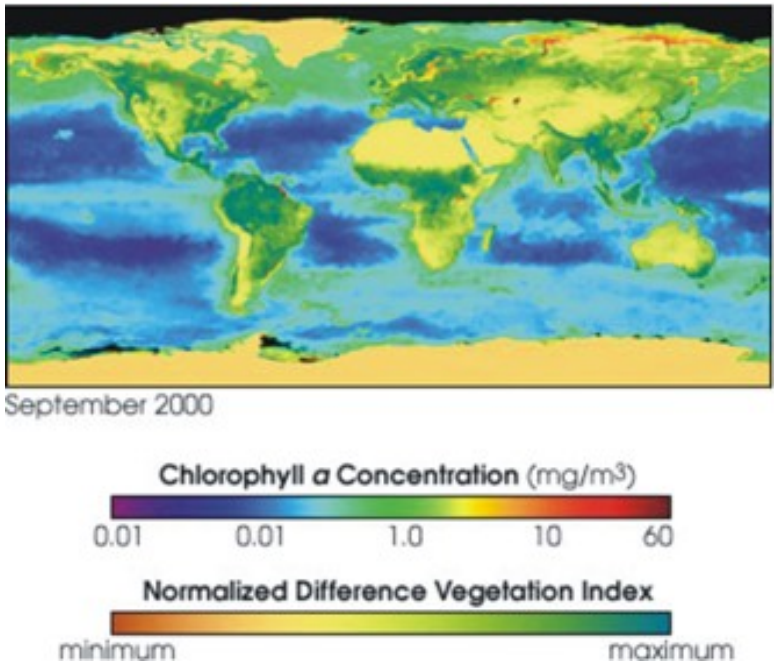

Figure 15.1: This image of Earth's surface shows the density of the chief life forms that produce food for other organisms in the biosphere. Plants are the chief food producers on land, and phytoplankton are the chief food producers in the ocean. The map shows the density of plants with a measure called the normalized difference vegetation index and the density of phytoplankton with the chlorophyll concentration.

- rapid decline in populations of many nonhuman species, which has led to the extinction of numerous species.

Another level at which ecologists study organisms and their environments is the community level. A **community** consists of populations of different species that live in the same area and interact with one another. For example, populations of coyotes and rabbits might interact in a grassland community. Coyotes hunt down and eat rabbits for food, so the two species have a predator-prey relationship. Ecological issues at the community level include how changes in the size of one population affect other populations. The *Populations* chapter discusses population interactions in communities in detail.

Ecosystem

A community can also be defined as the biotic component of an ecosystem. An **ecosystem** is a natural unit consisting of all the living organisms in an area functioning together with all the nonliving physical factors of the environment. The concept of an ecosystem can apply to units of different sizes. For example, a large body of fresh water could be considered an ecosystem, and so could a small piece of dead wood. Both contain a community of species that interact with one another and with the abiotic components of their environment. Another example of an ecosystem is a desert, like the one shown in **Figure** 15.2.

Like most natural systems, ecosystems are not closed, at least not in terms of energy. Ecosystems depend on continuous inputs of energy from outside the system. Most ecosystems obtain energy from sunlight. Some obtain energy from chemical compounds. In Lesson 2, you will read how energy is transferred in ecosystems. In contrast to energy, matter is recycled in ecosystems. Elements such as carbon and nitrogen, which are needed by living organisms, are used over and over again. You will read how elements and water are recycled through ecosystems in Lesson 3.

Niche

One of the most important ideas associated with ecosystems is the niche concept. A **niche** refers to the role of a species in its ecosystem. It includes all the ways species' members interact with the abiotic and biotic components of the ecosystem.

Two important aspects of a species' niche include the food it eats and how it obtains the food. **Figure** 15.3 shows pictures of birds that occupy different niches. The various species eat different types of food and obtain the food in different ways. Notice how each species has evolved a beak that suits it for these aspects of its niche.

Figure 15.2: This desert ecosystem in southern California has fewer species than most other types of ecosystems, but it is still home to a community of interacting species (such as the cacti and grasses shown here) and potent environmental factors such as extreme heat and dryness.

Habitat

Another aspect of a species' niche is its habitat. A species' **habitat** is the physical environment to which it has become adapted and in which it can survive. A habitat is generally described in terms of abiotic factors, such as the average amount of sunlight received each day, the range of annual temperatures, and average yearly rainfall. These and other factors in a habitat determine many of the traits of the organisms that can survive there.

Consider a habitat with very low temperatures. Mammals that live in the habitat must have insulation to help them stay warm. Otherwise, their body temperature will drop to a level that is too low for survival. Species that live in these habitats have evolved fur, blubber, and other traits that provide insulation in order for them to survive in the cold.

Human destruction of habitats is the major factor causing other species to decrease and become endangered or go extinct. Small habitats can support only small populations of organisms. Small populations are more susceptible to being wiped out by catastrophic events from which a large population could bounce back. Habitat destruction caused the extinction of the dusky seaside sparrow shown in **Figure** 15.4. Many other bird species are currently declining worldwide. More than 1,200 species face extinction during the next century due mostly to habitat loss and climate change.

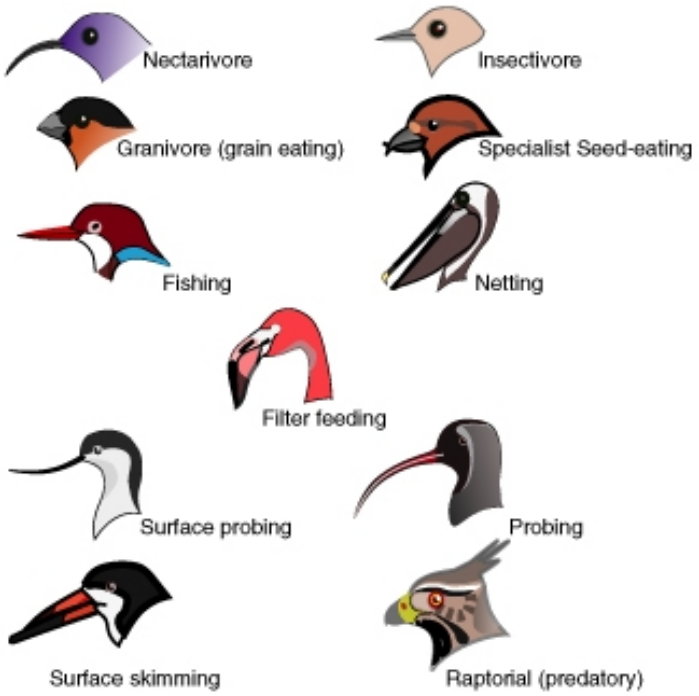

Figure 15.3: Each of these 11 species of birds has a distinctive beak that suits it for its particular niche. For example, the long slender beak of the Nectarivore allows it to sip nectar from flowers, and the short sturdy beak of the Granivore allows it to crush hard, tough grains.

Figure 15.4: The dusky seaside sparrow, which used to live in marshy areas of southern Florida, was declared extinct in 1990.

Competitive Exclusion Principle

A given habitat may contain many different species, each occupying a different niche. However, two different species cannot occupy the same niche in the same geographic area for very long. This is known as the **competitive exclusion principle**. It is another basic principle of ecology. If two species were to occupy the same niche, they would compete with one another for the same food and other resources in the environment. Eventually, one species would outcompete and replace the other.

Humans often introduce new species into areas where their niches are already occupied by native species. This may occur intentionally or by accident. Consider the example of kudzu. Kudzu is a Japanese vine that was introduced intentionally to the southeastern United States in the 1870s to help control soil erosion. The southeastern United States turned out to be a perfect habitat for kudzu, because it has no natural enemies there. As a result, kudzu was able to outcompete native species of vines and take over their niches. The extent to which kudzu has invaded some habitats in the southeastern United States is shown in **Figure** 15.5.

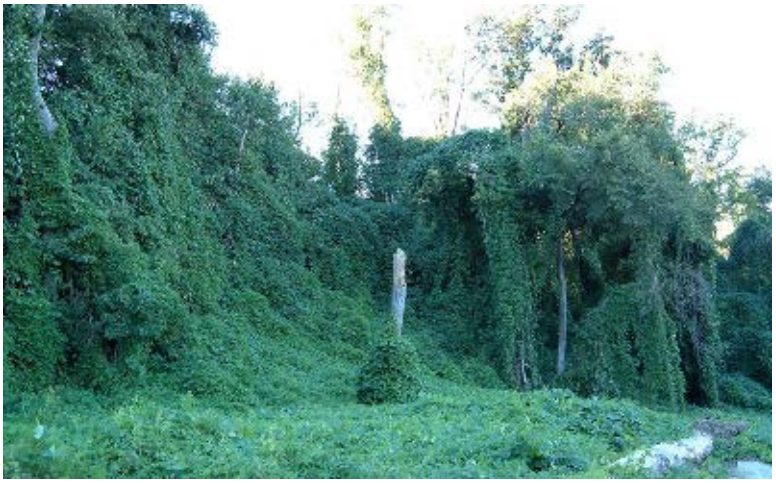

Figure 15.5: Kudzu covers the trees in this habitat near Atlanta, Georgia, in the southeastern United States. Native species of vines cannot compete with kudzu's thriving growth and lack of natural enemies.

Methods of Ecology

Ecology is more holistic, or all-encompassing, than some other fields of biology. Ecologists study both biotic and abiotic factors and how they interact. Therefore, ecologists often use methods and data from other areas of science, such as geology, geography, climatology, chemistry, and physics. In addition, researchers in ecology are more likely than researchers in some other sciences to use field studies to collect data.

Field Studies

Ecological research often includes field studies because ecologists generally are interested in the natural world. **Field studies** involve the collection of data in real-world settings, rather than in controlled laboratory settings. The general aim of field studies is to collect observations in wild populations without impacting the environment or its organisms in any way.

Ecologists commonly undertake field studies to determine the numbers of organisms of particular species in a given geographic area. Such studies are useful for a variety of purposes. For example, the data might help an ecologist decide whether a given species is in danger of extinction.

Sampling

In field studies, it usually is not possible to investigate all the organisms in an area. Therefore, some type of sampling scheme is generally necessary. For example, assume an ecologist wants to find the number of insects of a particular species in a given area. There may be thousands of members of the species in the area. So, for practical reasons, the ecologist might count only a sample of the insects. In order to select the sample, the ecologist could divide the entire area into a grid of one-meter-square test plots. Then the ecologist might systematically select every tenth (or other numbered) test plot and count all the insects in the plot.

Statistical Analysis

Like other scientists, ecologists may use two different types of statistical analysis to interpret the data they collect: descriptive statistics and inferential statistics. **Descriptive statistics** are used to describe data. For example, the ecologist studying insects might calculate the mean number of insects per test plot and find that it is 24. This descriptive statistic summarizes the counts from all the test plots in a single number. Other descriptive statistics, such as the range, describe variation in data. The **range** is the difference between the highest and lowest values in a sample. In the same example, if the numbers of insects per test plot ranged from 2 to 102, the range would be 100.

Scientists often want to make inferences about a population based on data from a sample. For example, the ecologist counting insects might want to estimate the number of insects in the entire area based on data for the test plots sampled. Drawing inferences about a population from a sample requires the use of inferential statistics. **Inferential statistics** can be used to determine the chances that a sample truly represents the population from which it was drawn. It tells the investigator how much confidence can be placed in inferences about the population that are based on the sample.

Modeling

Ecologists, like other scientists, often use models to help understand complex phenomena. Ecological systems are often modeled using computer simulations. Computer simulations can incorporate many different variables and their interactions. This is one reason they are useful for modeling ecological systems. Computer simulations are also working models, so they can show what may happen in a system over time. Simulations can be used to refine models, test hypotheses, and make predictions. For example, simulations of global warming have been used to make predictions about future climates.

Lesson Summary

- Ecology is the scientific study of living things and their relationships with the environment. Levels of organization in ecology include the biosphere, population, community, and ecosystem.
- An ecosystem is a natural unit consisting of all the living organisms in an area functioning together with all the non-living physical factors of the environment. Each species has a unique role in an ecosystem, called its niche. The physical environment where a species lives is its habitat.
- Ecologists use field studies and sampling schemes to gather data in natural environments. Like other scientists, ecologists use statistics to describe and make inferences from data. They also use computer simulations to model complex phenomena.

Review Questions

1. Define abiotic and biotic components of the environment.
2. What does the biosphere consist of?
3. How do ecologists define an ecosystem?
4. What does the competitive exclusion principle state?
5. Assume an ecologist is studying interactions among different species in an ecosystem. What level of organization should the ecologist study? Why?
6. Why are field studies and computer simulations important methods of investigation in ecology?
7. Compare and contrast the ecosystem concepts of niche and habitat.

Further Reading / Supplemental Links

- Desonie, Dana, Biosphere: *Ecosystems and Biodiversity Loss.* Chelsea House Publications, 2007.
- Novacek, Michael, Terra: *Our 100-Million-Year-Old Ecosystem and the Threats That Now Put It at Risk.* Farrar, Straus, and Giroux, 2007.

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- http://www.science.doe.gov/ober/CCRD/model.html
- http://interactive2.usgs.gov/learningweb/explorer/topic_eco.htm
- http://www.dmoz.org/Science/Biology/Ecology/
- http://www.enviroliteracy.org/category.php/3.html
- http://www.sciencedaily.com/news/earth_climate/ecosystems/
- http://www.soinc.org/events/ecology/index.htm
- http://www.topix.net/science/ecology
- http://en.wikipedia.org

Vocabulary

abiotic components The non-living physical aspects of the environment; includes sunlight, soil, temperature, wind, water, and air; also known as abiotic factors.

biosphere The areas of Earth where all organisms live; extends from about 11,000 meters below sea level to 15,000 meters above sea level.

biotic components The living organisms in the environment; also known as biotic factors.

community Populations of different species that live in the same area and interact with one another.

competitive exclusion principle States that two different species cannot occupy the same niche in the same geographic area for very long.

descriptive statistics Statistical analysis used to describe data.

ecology The scientific study of the interactions of living things with each other and their relationships with the environment.

ecosystem A natural unit consisting of all the living organisms in an area functioning together with all the nonliving physical factors of the environment.

field studies Studies that involve the collection of data in real-world settings, rather than in controlled laboratory settings; allows observations of wild populations without impacting the environment or its organisms in any way.

habitat The physical environment to which an organism has become adapted and in which it can survive.

inferential statistics Statistical analysis that draws inferences about a population from a sample; used to determine the chances that a sample truly represents the population from which it was drawn.

niche The role of a species in its ecosystem; includes all the ways species' members interact with the abiotic and biotic components of the ecosystem.

organism A life form consisting of one or more cells.

population Organisms of the same species that live in the same area and interact with one another.

range Statistic used to describe the difference between the highest and lowest values in a sample.

Points to Consider

An ecosystem needs continuous inputs of energy in order for its organisms to survive. In most ecosystems, this energy comes from sunlight.

- Which organisms in an ecosystem capture the energy from sunlight? How do they transform the energy so that other organisms in the ecosystem can use it? Why is the energy that enters an ecosystem eventually used up?

15.2 Lesson 15.2: Flow of Energy

Lesson Objectives

- Describe how autotrophs use energy to produce organic molecules.
- Identify different types of consumers, and give examples of each type.
- Explain how decomposers resupply elements to producers.
- Describe food chains and food webs, and explain how energy is transferred between their trophic levels.

Introduction

Energy enters most ecosystems from sunlight. However, some ecosystems, such as hydrothermal vent ecosystems at the bottom of the ocean, receive no sunlight and obtain energy instead from chemical compounds. Energy is used by some organisms in the ecosystem to make food. These organisms are called primary producers, or autotrophs, which include small plants, algae, photosynthetic prokaryotes and chemosynthetic prokaryotes. From primary producers, energy eventually is transferred to all the other organisms in the ecosystem through consumers or decomposers known as heterotrophs.

Producers

Producers are organisms that produce organic compounds from energy and simple inorganic molecules. Producers are also called **autotrophs**, which literally means "self nutrition." This is because producers synthesize food for themselves. They take energy and materials from the abiotic environment and use them to make organic molecules. Autotrophs are a vital part of all ecosystems. The stability of the producers is vital to the survival of every ecosystem; without this stability an ecosystem may not thrive; in fact, the ecosystem may collapse. The organic molecules the producers make are needed by all the organisms in the ecosystem. There are two basic types of autotrophs: photoautotrophs and chemoautotrophs. They differ in the type of energy they use to synthesize food.

Photoautotrophs

Photoautotrophs are organisms that use energy from sunlight to make food by photosynthesis. As you may recall from the *Photosynthesis* Chapter, **photosynthesis** is the process by which carbon dioxide and water are converted to glucose and oxygen, using sunlight for energy. Glucose, a carbohydrate, is an organic compound that can be used by autotrophs and other organisms for energy. As shown in **Figure** 15.6, photoautotrophs include plants, algae, and certain bacteria.

Plants are the most important photoautotrophs in land-based, or terrestrial, ecosystems. There is great variation in the plant kingdom. Plants include organisms as different as trees, grasses, mosses, and ferns. Nonetheless, all plants are eukaryotes that contain chloroplasts, the cellular "machinery" needed for photosynthesis.

Algae are photoautotrophs found in most ecosystems, but they generally are more important in water-based, or aquatic, ecosystems. Like plants, algae are eukaryotes that contain chloroplasts for photosynthesis. Algae include single-celled eukaryotes, such as diatoms, as well as multicellular eukaryotes, such as seaweed.

Photoautotrophic bacteria, called **cyanobacteria**, are also important producers in aquatic ecosystems. Cyanobacteria were formerly called *blue-green algae*, but they are now classified

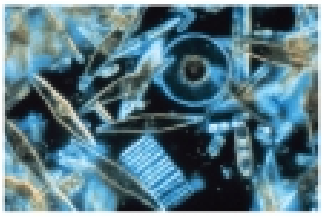
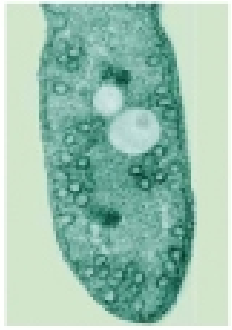
Photoautotrophs and Ecosystems Where They are Found		
Type of Photoautotroph	**Examples**	**Type of Ecosystem(s)**
Plants	 Trees  Grasses	Terrestrial
Algae	 Diatoms  Seaweed	Aquatic
Bacteria	 Cyanobacteria  Purple Bacteria	Aquatic Terrestrial

Figure 15.6: Different types of photoautotrophs are important in different types of ecosystems. Each type of photoautotroph pictured here is an important producer in some ecosystem.

as bacteria. Other photosynthetic bacteria, including purple photosynthetic bacteria, are producers in terrestrial as well as aquatic ecosystems.

Both cyanobacteria and algae make up **phytoplankton**. Phytoplankton refers to all the tiny photoautotrophs found on or near the surface of a body of water. Phytoplankton usually is the primary producer in aquatic ecosystems.

Chemoautotrophs

In some places where life is found on Earth, there is not enough light to provide energy for photosynthesis. In these places, producers called **chemoautotrophs** use the energy stored in chemical compounds to make organic molecules by chemosynthesis. **Chemosynthesis** is the process by which carbon dioxide and water are converted to carbohydrates. Instead of using energy from sunlight, chemoautotrophs use energy from the oxidation of inorganic compounds, such as hydrogen sulfide (H_2S). Oxidation is an energy-releasing chemical reaction in which a molecule, atom, or ion loses electrons.

Chemoautotrophs include bacteria called nitrifying bacteria, which you will read more about in Lesson 3. Nitrifying bacteria live underground in soil. They oxidize nitrogen-containing compounds and change them to a form that plants can use.

Chemoautotrophs also include archaea. **Archaea** are a domain of microorganisms that resemble bacteria. Most archaea live in extreme environments, such as around hydrothermal vents in the deep ocean. Hot water containing hydrogen sulfide and other toxic substances escapes from the ocean floor at these vents, creating a hostile environment for most organisms. Near the vents, archaea cover the sea floor or live in or on the bodies of other organisms, such as tube worms. In these ecosystems, archaea use the toxic chemicals released from the vents to produce organic compounds. The organic compounds can then be used by other organisms, including tube worms. Archaea are able to sustain thriving communities, like the one shown in **Figure** 15.7, even in these hostile environments.

Consumers

Consumers are organisms that depend on producers or other types of organisms for food. They are also called **heterotrophs**, which literally means "other nutrition." Heterotrophs are unable to make organic compounds from inorganic molecules and energy. Instead, they take in organic molecules by consuming other organisms. All animals and fungi and many bacteria are heterotrophs. A few insect-eating plants are also heterotrophic. Heterotrophs can be classified on the basis of the types of organisms they consume. They include herbivores, omnivores, and carnivores.

Figure 15.7: Red tube worms, each containing millions of archaea microorganisms, grow in a cluster around a hydrothermal vent in the deep ocean floor. Archaea produce food for themselves (and for the tube worms) by chemosynthesis.

Herbivores

Herbivores are organisms that consume only producers such as plants or algae. In most ecosystems, herbivores form a necessary link between producers and other consumers. Herbivores transform the energy stored in producers to compounds that can be used by other organisms.

In terrestrial ecosystems, many animals and fungi and some bacteria are herbivores. Herbivorous animals include deer, rabbits, and mice. Herbivores may specialize in particular types of plants, such as grasses, or specific plant parts, such as leaves, nectar, or roots. Examples of herbivores are shown in **Figure** 15.8.

In aquatic ecosystems, the main herbivores are the heterotrophic organisms that make up zooplankton. **Zooplankton** refers to all the small organisms that feed on phytoplankton. These organisms include both single-celled organisms such as protozoa and multicellular organisms such as jellyfish. Phytoplankton and zooplankton together make up large communities of producers and herbivores called **plankton**.

Carnivores

Carnivores are organisms that eat a diet consisting mainly of herbivores or other carnivores. Carnivores include lions, wolves, polar bears, hawks, frogs, fish, and spiders. Animals that eat only meat are called obligate carnivores. They generally have a relatively short digestive system that cannot break down the tough cellulose found in plants. Other carnivores, including dogs, can digest plant foods but do not commonly eat them. Certain carnivores, called **scavengers**, mainly eat the carcasses of dead animals. Scavengers include vultures, raccoons, and blowflies.

A tiny minority of plants—including Venus flytraps and pitcher plants—are also carnivorous. These plants trap and digest insects. Some fungi are carnivorous as well. Carnivorous fungi capture and digest microscopic protozoan organisms such as amoebas.

Omnivores

Omnivores are organisms that eat both plants and animals as primary food sources. Humans are an example of an omnivorous species. Although some humans eat foods derived only from plants or only from animals, the majority of humans eat foods from both sources. Other examples of omnivorous animals are pigs, brown bears, gulls, and crows. Aquatic omnivores include some species of fish, such as piranhas.

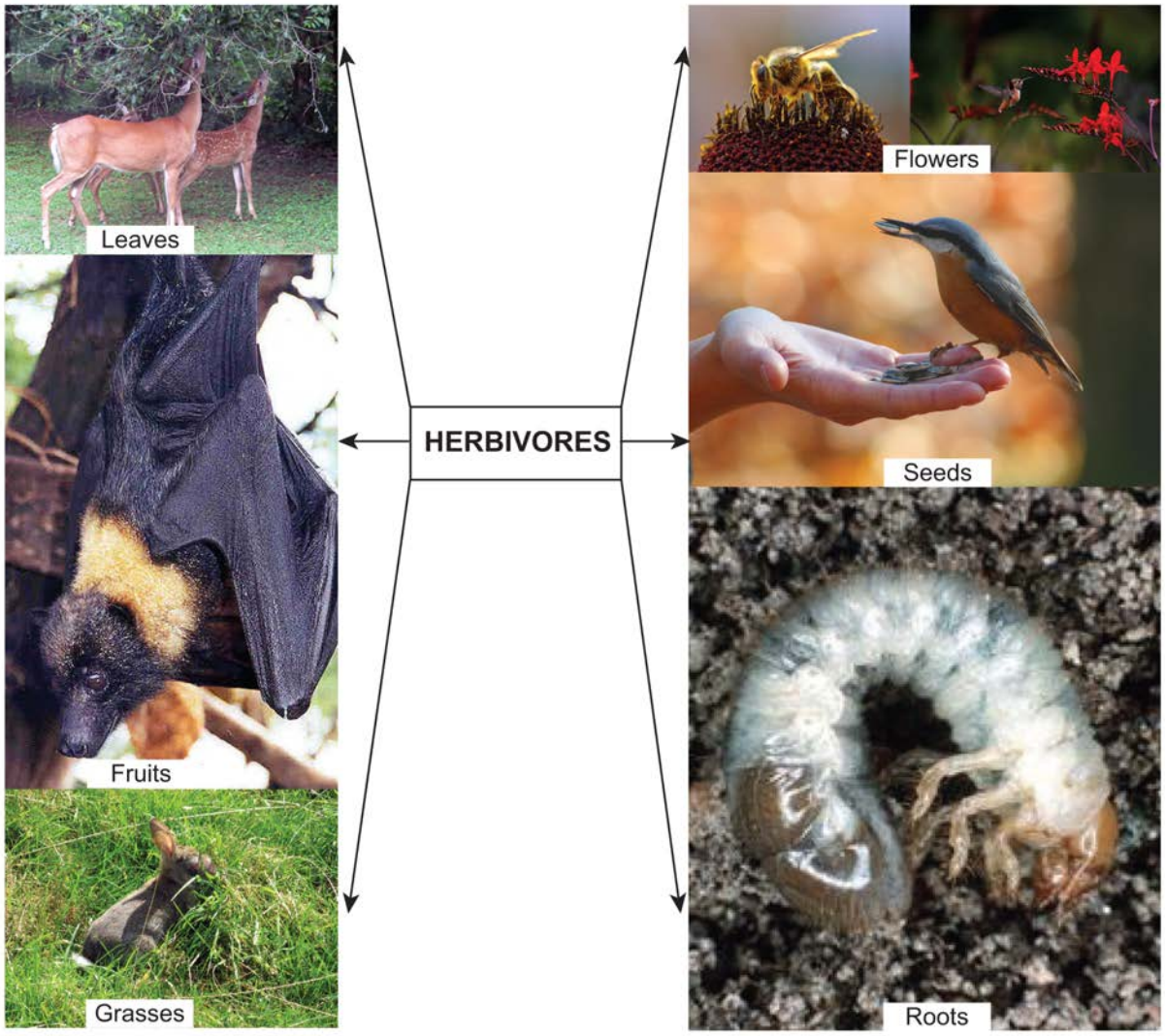


Figure 15.8: Deer browse on leaves. A hummingbird sips nectar from a flower. A bee gathers pollen from a flower. Many bats, including this one, primarily eat fruit. Some birds mainly eat seeds. A rabbit eats grasses. Beetle larvae like this one eat plant roots.

Decomposers

When a plant or animal dies, it leaves behind energy and matter in the form of the organic compounds that make up its remains. **Decomposers** are organisms that consume dead organisms and other organic waste. They recycle materials from the dead organisms and waste back into the ecosystem. These recycled materials are used by the producers to remake organic compounds. Therefore, decomposers, like producers, are an essential part of every ecosystem, and their stability is essential to the survival of each ecosystem. In essence, this process completes and restarts the "circle of life." As stated above, scavengers consume the carcasses of dead animals. The remains of dead plants are consumed by organisms called detritivores.

Detritivores

When plants drop leaves or die, they contribute to detritus. **Detritus** consists of dead leaves and other plant remains that accumulate on the ground or at the bottom of a body of water. Detritus may also include animal feces and other organic debris. Heterotrophic organisms called **detritivores** feed on detritus. Earthworms, millipedes, and woodlice are detritivores that consume rotting leaves and other dead plant material in or on soil. Dung beetles, like the one shown in **Figure 4**, consume feces. In aquatic ecosystems, detritivores include "bottom feeders," such as sea cucumbers and catfish.

Figure 15.9: Dung beetle rolling a ball of feces to its nest to feed its offspring.

Saprotrophs

After scavengers and detritivores feed on dead organic matter, some unused energy and organic compounds still remain. For example, scavengers cannot consume bones, feathers, and fur of dead animals, and detritivores cannot consume wood and other indigestible plant material. Organisms called **saprotrophs** complete the breakdown of any remaining organic matter. The main saprotrophs that decompose dead animal matter are bacteria. The main saprotrophs that decompose dead plant matter are fungi. Fungi are also the only organisms that can decompose dead wood. Single-celled protozoa are common saprotrophs in aquatic ecosystems as well as in soil.

Saprotrophs convert dead organic material into carbon dioxide and compounds containing nitrogen or other elements needed by living organisms. The elements are then available to be used again by producers for the synthesis of organic compounds.

Food Chains and Food Webs

Food chains and food webs represent the feeding relationships in ecosystems. They show who eats whom. Therefore, they model the flow of energy and materials through ecosystems.

Food Chains

A **food chain** represents a simple linear pathway through which energy and materials are transferred from one species to another in an ecosystem. In general, food chains show how energy and materials flow from producers to consumers. Energy and materials also flow from producers and consumers to decomposers, but this step usually is not included in food chains. Two examples of food chains are shown in **Figure** 15.10.

Food Webs

Food chains tend to be overly simplistic representations of what really happens in nature. Most organisms consume multiple species and are, in turn, consumed by multiple other species. A food web represents these more complex interactions. A **food web** is a diagram of feeding relationships that includes multiple intersecting food chains. An example of a food web is shown in **Figure** 15.11.

In the food web in **Figure** 15.11, phytoplankton is the producer, and zooplankton is the primary consumer. Secondary consumers, which eat zooplankton, include salmon, cephalopods, sand lances, and auklets. Puffins, kittiwakes, and gulls are tertiary consumers. Foxes, rats, and gulls are quaternary consumers. Two possible food chains within this food web are:

Fox → Puffin → Cephalopod → Zooplankton → Phytoplankton;

Trophic Level	Terrestrial (Grassland) Food Chain	Aquatic (Ocean) Food Chain
Quaternary Consumer	Hawk 	White Shark 
Tertiary Consumer	Snake 	Seal 
Secondary Consumer	Mouse 	Fish 
Primary Consumer	Grasshopper 	Zooplankton 
Producer	Grass 	Phytoplankton 

Figure 15.10

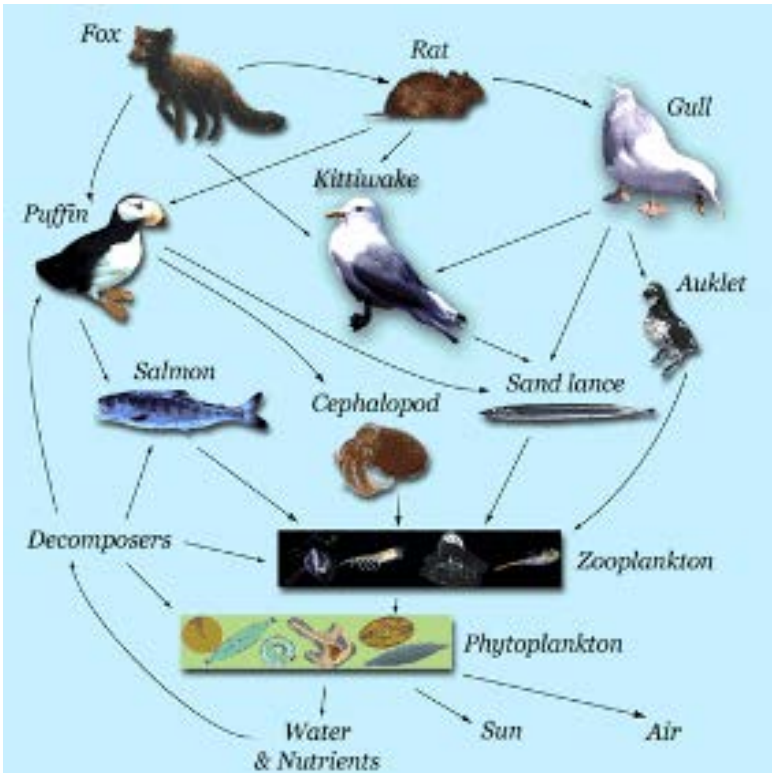


Figure 15.11: This aquatic food web consists of several intersecting food chains. Which organisms are producers in all the food chains included in the food web?

Rat → Kittiwake → Sand lance → Zooplankton → Phytoplankton.

Can you identify other food chains in this food web?

Trophic Levels and Energy Transfer

The different feeding positions in a food chain or web are called **trophic levels**. The first trophic level consists of producers, the second of primary consumers, the third of secondary consumers, and so on. There usually are no more than four or five trophic levels in a food chain or web. Humans may fall into second, third, and fourth trophic levels of food chains or webs. They eat producers such as grain, primary consumers such as cows, and tertiary consumers such as salmon.

Energy is passed up the food chain from one trophic level to the next. However, only about 10 percent of the total energy stored in organisms at one trophic level is actually transferred to organisms at the next trophic level. The rest of the energy is used for metabolic processes or lost to the environment as heat. As a result, less energy is available to organisms at each successive trophic level. This explains why there are rarely more than four or five trophic levels. The amount of energy at different trophic levels can be represented by an energy pyramid like the one in **Figure** 15.12.

Pyramid of Energy

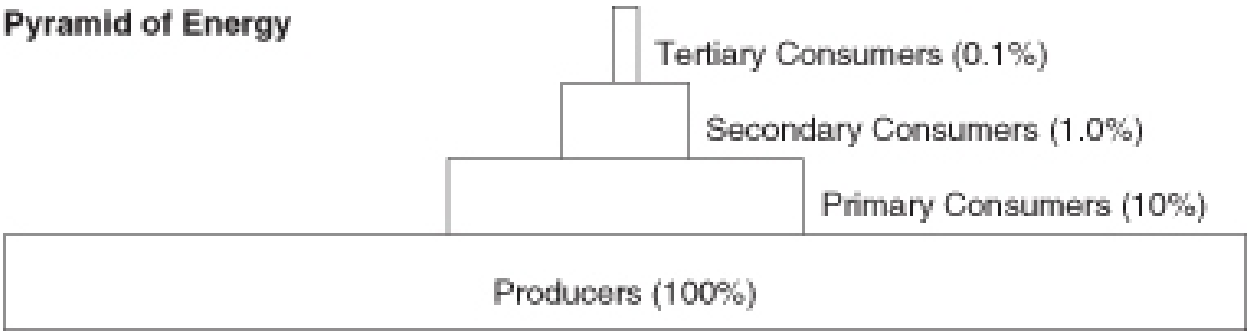


Figure 15.12: This pyramid shows the total energy stored in organisms at each trophic level in an ecosystem. Starting with primary consumers, each trophic level in the food chain has only 10 percent of the energy of the level below it. The pyramid makes it clear why there can be only a limited number of trophic levels in a food chain or web.

Because there is less energy at higher trophic levels, there are usually fewer organisms as well. Organisms tend to be larger in size at higher trophic levels, but their smaller numbers still result in less biomass. **Biomass** is the total mass of organisms in a trophic level (or other grouping of organisms). The biomass pyramid in **Figure** 15.13 shows how biomass of organisms changes from first to higher trophic levels in a food chain.

Pyramid of Biomass

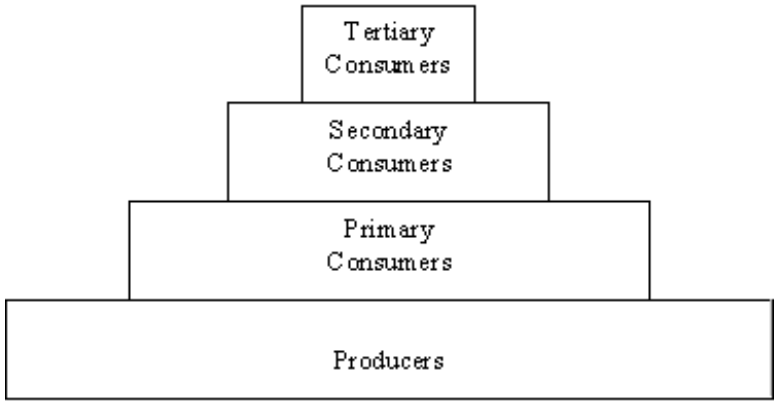


Figure 15.13: This pyramid shows the total biomass, or mass of organisms, at each trophic level in an ecosystem. How does this pyramid relate to the energy pyramid in ?

The materials in dead organisms and wastes at all trophic levels are broken down by decomposers. Organisms such as detritivores and saprotrophs return needed elements to the ecosystem and use up most remaining energy. Because of the reduction in energy at each trophic level, virtually no energy remains. Therefore, energy must be continuously added to ecosystems by producers.

Lesson Summary

- Producers in ecosystems are autotrophs. They use energy from sunlight or chemical compounds to synthesize organic molecules from carbon dioxide and other simple inorganic molecules.
- Consumers in ecosystems are heterotrophs, or organisms that consume other organisms for food. Consumers include herbivores such as deer, carnivores such as lions, and omnivores such as humans.
- Decomposers break down dead organisms and other organic wastes in ecosystems. They resupply producers with the elements they need to synthesize organic compounds.
- Food chains and food webs model feeding relationships in ecosystems. They show how energy and materials are transferred between trophic level when consumers eat producers or other organisms.

Review Questions

1. How do autotrophs use energy to produce organic molecules?
2. Define three different types of consumers, and name an example of each.
3. How do decomposers resupply elements to producers?
4. How is energy transferred between trophic levels in a food chain?

5. In Figure 6, identify two food chains containing gulls: one in which gulls are tertiary consumers, and one in which gulls are quaternary consumers.
6. If one million kilocalories of energy are stored in producers in an ecosystem, how many kilocalories can be transferred to tertiary consumers in the ecosystem? Show the calculations that support your answer.
7. Draw a terrestrial food chain that includes four trophic levels.
8. All organisms consist of carbon compounds. Infer how the amount of carbon stored in organisms changes from one trophic level to the next. Explain your answer.

Further Reading / Supplemental Links

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Vocabulary

Archaea A prokaryotic domain of microorganisms that resemble bacteria; most archaea live in extreme environments, such as around hydrothermal vents in the deep ocean and are chemoautotrophs.

autotrophs Organisms that produce organic compounds from energy and simple inorganic molecules; also known as producers.

carnivores Organisms that eat a diet consisting mainly of herbivores or other carnivores.

chemoautotrophs Organisms that use the energy stored in chemical compounds to make organic molecules by chemosynthesis.

chemosynthesis The process by which carbon dioxide and water are converted to carbohydrates; uses energy from the oxidation of inorganic compounds.

consumers Organisms that depend on producers or other types of organisms for food.

decomposers Organisms that consume dead organisms and other organic waste.

detritivores Organisms that consume the remains of dead plants (detritus).

detritus Dead leaves and other plant remains that accumulate on the ground or at the bottom of a body of water.

food chain A simple linear pathway through which energy and materials are transferred from one species to another in an ecosystem.

food web A diagram of feeding relationships that includes multiple intersecting food chains.

herbivores Organisms that consume only producers such as plants or algae; form a necessary link between producers and other consumers.

heterotrophs Organisms that depend on producers or other types of organisms for food; also called consumers.

omnivores Organisms that eat both plants and animals as primary food sources.

oxidation An energy-releasing chemical reaction in which a molecule, atom, or ion loses electrons.

photoautotrophs Organisms that use energy from sunlight to make food by photosynthesis; includes plants, algae, and certain bacteria.

photosynthesis The process by which carbon dioxide and water are converted to glucose and oxygen, using sunlight for energy.

phytoplankton All the tiny photoautotrophs found on or near the surface of a body of water; usually is the primary producer in aquatic ecosystems; includes both cyanobacteria and algae.

plankton Large communities of producers and herbivores; made up of phytoplankton and zooplankton.

producers Organisms that produce organic compounds from energy and simple inorganic molecules.

saprotrophs Organisms that complete the breakdown of any remaining organic matter, such as bones, feathers, and fur of dead animals, and wood and other indigestible plant material.

scavengers Carnivores that mainly eat the carcasses of dead animals.

trophic levels The different feeding positions in a food chain or web.

zooplankton All the small organisms that feed on phytoplankton; includes both single-celled organisms such as protozoa and multicellular organisms such as jellyfish.

Points to Consider

Matter recycles through the biotic components of ecosystems as producers synthesize organic compounds and other organisms consume the compounds.

- Do you think abiotic components of ecosystems also play roles in recycling matter?
- What abiotic components do you think might be involved? For example, what abiotic components do you think might be involved in the cycling of water?

15.3 Lesson 15.3: Recycling Matter

Lesson Objectives

- Define and give examples of biogeochemical cycles that recycle matter.
- Describe the water cycle and the processes by which water changes state.
- Summarize the organic and geological pathways of the carbon cycle.
- Outline the nitrogen cycle and state the roles of bacteria in the cycle.

Introduction

Unlike energy, elements are not lost and replaced as they pass through ecosystems. Instead, they are recycled repeatedly. All chemical elements that are needed by living things are recycled in ecosystems, including carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulfur. Water is also recycled.

Biogeochemical Cycles

A biogeochemical cycle is a closed loop through which a chemical element or water moves through ecosystems. In the term *biogeochemical, bio-* refers to biotic components and *geo-* to geological and other abiotic components. Chemicals cycle through both biotic and abiotic components of ecosystems. For example, an element might move from the atmosphere to ocean water, from ocean water to ocean organisms, and then back to the atmosphere to repeat the cycle.

Elements or water may be held for various lengths of time by different components of a biogeochemical cycle. Components that hold elements or water for a relatively short period of time are called exchange pools. For example, the atmosphere is an exchange pool for water. It holds water for several days at the longest. This is a very short time compared with the thousands of years the deep ocean can hold water. The ocean is an example of a reservoir for water. Reservoirs are components of a geochemical cycle that hold elements or water for a relatively long period of time.

Water Cycle

Earth's water is constantly in motion. Although the water on Earth is billions of years old, individual water molecules are always moving through the water cycle. The **water cycle** describes the continuous movement of water molecules on, above, and below Earth's surface. It is shown in **Figure** 15.14. Like other biogeochemical cycles, there is no beginning or end to the water cycle. It just keeps repeating. During the cycle, water occurs in its three different states: gas (water vapor), liquid (water), and solid (ice). Processes involved in changes of state in the water cycle include evaporation, sublimation, and transpiration.

Evaporation, Sublimation, and Transpiration

The sun is the driving force behind the water cycle. It heats oceans, lakes, and other bodies of water, causing water to evaporate from the surface and enter the atmosphere as water vapor. Water in soil also evaporates easily. In addition, the sun heats ice and snow, causing it to turn directly into water vapor in the process of **sublimation**. Water also evaporates from the above-ground parts of plants. Transpiration is another process by which plants lose water. **Transpiration** occurs when stomata in leaves open to take in carbon dioxide for photosynthesis and lose water to the atmosphere in the process.

The water cycle plays an important role in climate. For molecules of liquid water to change to water vapor, kinetic energy is required, or the energy of movement. As faster-moving molecules evaporate, the remaining molecules have lower average kinetic energy, and the temperature of ocean water thus decreases. The primary way that oceans slow global warming is by heat uptake which warms ocean water and removes some energy from the atmosphere.

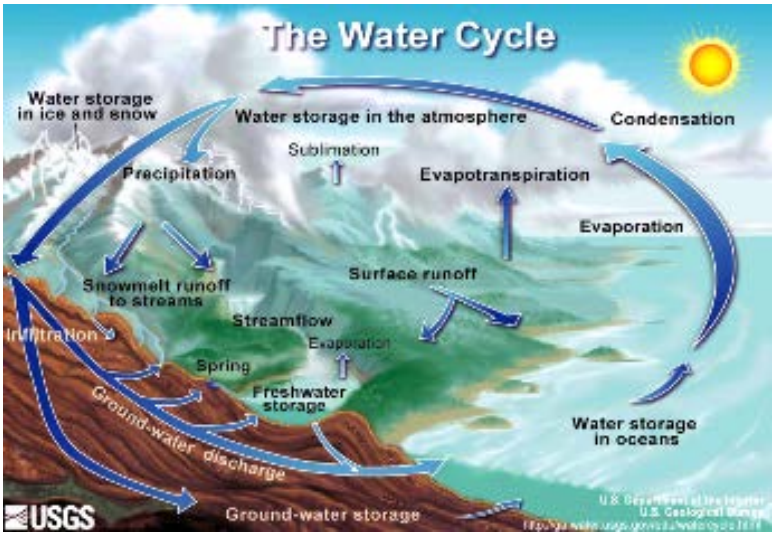

Figure 15.14: This diagram of the water cycle shows where water is stored and the processes by which water moves through the cycle, including evaporation, condensation, and precipitation.

Condensation and Precipitation

Rising air currents carry water vapor from all these sources into the atmosphere. As the water vapor rises higher into the atmosphere or is carried toward the poles by winds, the air becomes cooler. Cooler air cannot hold as much water vapor, so the water vapor condenses into tiny water droplets around particles in the air. The tiny water droplets form clouds.

Air currents cause the tiny water droplets in clouds to collide and merge into larger droplets. When water droplets in clouds become large enough to fall, they become **precipitation**. Most precipitation falls back into the ocean. Precipitation that falls at high altitudes or near the poles can accumulate as ice caps and glaciers. These masses of ice can store frozen water for hundreds of years or longer.

Infiltration and Runoff

Rain that falls on land may either soak into the ground, which is called **infiltration**, or flow over the land as **runoff**. Snow that falls on land eventually melts, with the exception of snow that accumulates at high altitudes or near the poles. Like rain water, snowmelt can either infiltrate the ground or run off.

Water that infiltrates the ground is called **groundwater**. Groundwater close to the surface can be taken up by plants. Alternatively, it may flow out of the ground as a spring or slowly seep from the ground into bodies of water such as ponds, lakes, or the ocean. Groundwater can also flow deeper underground. It may eventually reach an aquifer. An **aquifer** is an

underground layer of water-bearing, permeable rock. Groundwater may be stored in an aquifer for thousands of years. Wells drilled into an aquifer can tap this underground water and pump it to the surface for human use.

Runoff water from rain or snowmelt eventually flows into streams and rivers. The water is then carried to ponds, lakes, or the ocean. From these bodies of water, water molecules can evaporate to form water vapor and continue the cycle.

Carbon Cycle

Runoff, streams, and rivers can gradually dissolve carbon in rocks and carry it to the ocean. The ocean is a major reservoir for stored carbon. It is just one of four major reservoirs. The other three are the atmosphere, the biosphere, and organic sediments such as fossil fuels. Fossil fuels, including petroleum and coal, form from the remains of dead organisms. All of these reservoirs of carbon are interconnected by pathways of exchange in the carbon cycle, which is shown in **Figure** 15.15.

Carbon occurs in a various forms in different parts of the carbon cycle. Some of the different forms in which carbon appears are described in **Table** 15.1. Refer to the table as you read how carbon moves between reservoirs of the cycle.

Table 15.1: **Forms of Carbon in the Carbon Cycle: Carbon Dioxide, Gas, Calcium Carbonate, Solids**

Form of Carbon	Chemical Formula	State	Main Reservoir
Carbon Dioxide	CO_2	Gas	Atmosphere
Carbonic Acid	H_2CO_3	Liquid	Ocean
Bicarbonate Ion	HCO_3^-	Liquid(dissolvedion)	Ocean
Organic Compounds	*Examples:* Glucose, $C_6H_{12}O_6$ Methane, CH_4	Solid Gas	Biosphere Organic Sediments (Fossil Fuels)
Other Carbon Compounds	*Examples:* Calcium Carbonate, $CaCO_3$ Calcium Magnesium Carbonate, $CaMg(CO_3)_2$	Solid Solid	Sedimentary Rock, Shells Sedimentary Rock

KEY: C = Carbon, O = Oxygen, H = Hydrogen

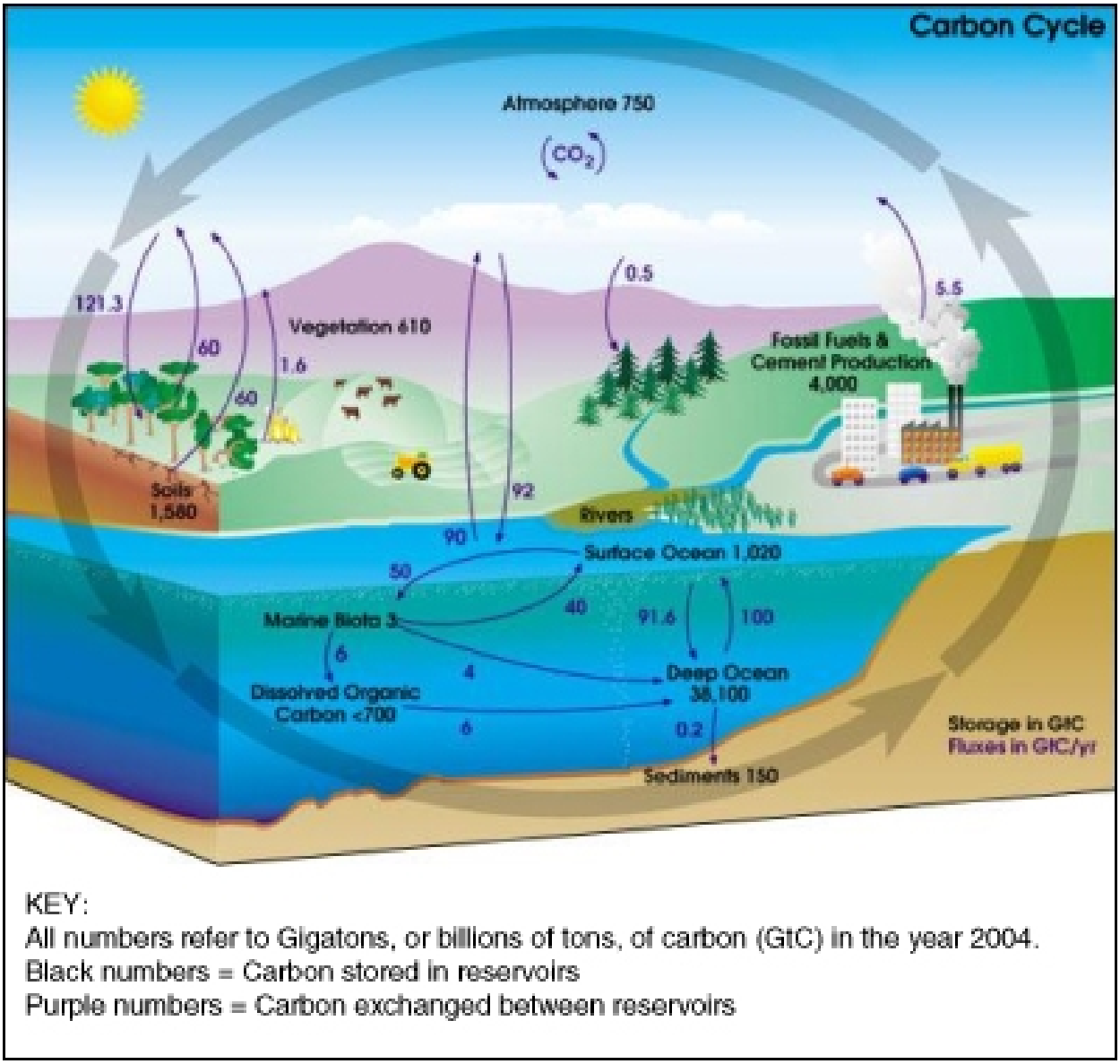

Figure 15.15: This drawing of the carbon cycle shows the amounts of carbon stored in and exchanged between carbon reservoirs on land and in water. Another 70 million GtC of carbon may be stored in sedimentary rock. If this is true, it would make sedimentary rock the greatest reservoir of carbon on Earth.

Carbon in the Atmosphere

In the atmosphere, carbon exists primarily as carbon dioxide (CO_2). Carbon dioxide enters the atmosphere from several different sources, including those listed below. Most of the sources are also represented in **Figure 2,** and some are described in detail later in the lesson.

- Living organisms release carbon dioxide as a byproduct of cellular respiration.
- Carbon dioxide is given off when dead organisms and other organic materials decompose.
- Burning organic material, such as fossil fuels, releases carbon dioxide.
- When volcanoes erupt, they give off carbon dioxide that is stored in the mantle.
- Carbon dioxide is released when limestone is heated during the production of cement.
- Ocean water releases dissolved carbon dioxide into the atmosphere when water temperature rises.

A much smaller amount of carbon in the atmosphere is present as methane gas (CH_4). Methane is released into the atmosphere when dead organisms and other organic matter decay in the absence of oxygen. It is produced by landfills, the mining of fossil fuels, and some types of agriculture.

There are also several different ways that carbon leaves the atmosphere. Carbon dioxide is removed from the atmosphere when plants and other autotrophs take in carbon dioxide to make organic compounds during photosynthesis or chemosynthesis. Carbon dioxide is also removed when ocean water cools and dissolves more carbon dioxide from the air. These processes are also represented in **Figure** 15.15.

Because of human activities, there is more carbon dioxide in the atmosphere today than in the past hundreds of thousands of years. Burning fossil fuels and producing concrete has released great quantities of carbon dioxide into the atmosphere. Cutting forests and clearing land has also increased carbon dioxide into the atmosphere because these activities reduce the number of autotrophic organisms that use up carbon dioxide in photosynthesis. In addition, clearing often involves burning, which releases carbon dioxide that was previously stored in autotrophs.

Carbon in Ocean Water

Most carbon enters the ocean when carbon dioxide in the atmosphere dissolves in ocean water. When carbon dioxide dissolves in water (H_2O), it forms an acid called carbonic acid (H_2CO_3). The reaction is given by the equation:

$CO_2 + H_2O \quad H_2CO_3$.

The double-headed arrow indicates that the reaction can occur in either direction, depending on the conditions and the amount of carbon dioxide present. For example, the reaction occurs more readily in the left-to-right direction in cold water. As a result, near the poles, where ocean water is cooler, more carbon dioxide is dissolved and there is more carbonic acid in the water. Although carbonic acid is a weak acid, it is an important regulator of the acid-base (pH) balance of ocean water.

Carbonic acid, in turn, readily separates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). This occurs in the following reaction:

$H_2CO_3 \quad H^+ + HCO_3^-$.

Due to these two reactions, most dissolved carbon dioxide in the ocean is in the form of bicarbonate ions. Another source of bicarbonate ions in ocean water is runoff. Flowing water erodes rocks containing carbon compounds such as calcium carbonate. This forms bicarbonate ions, which the runoff carries to streams, rivers, and eventually the ocean. Many of the bicarbonate ions in ocean water are moved by ocean currents into the deep ocean. Carbon can be held in this deep ocean reservoir as bicarbonate ions for thousands of years or more.

Carbon in the Biosphere

Bicarbonate ions near the surface of the ocean may be taken up by photosynthetic algae and bacteria that live near the surface. These and other autotrophic organisms use bicarbonate ions or other forms of carbon to synthesize organic compounds. Carbon is essential for life because it is the main ingredient of every type of organic compound. Organic compounds make up the cells and tissues of all organisms and keep organisms alive and functioning. Carbon enters all ecosystems, both terrestrial and aquatic, through autotrophs such as plants or algae. Autotrophs use carbon dioxide from the air, or bicarbonate ions from the water, to make organic compounds such as glucose. Heterotrophs consume the organic molecules and pass the carbon through food chains and webs.

How does carbon cycle back to the atmosphere or ocean? All organisms release carbon dioxide as a byproduct of cellular respiration. Recall from the *Cellular Respiration* chapter that **cellular respiration** is the process by which cells oxidize glucose and produce carbon dioxide, water, and energy. Decomposers also release carbon dioxide when they break down dead organisms and other organic waste.

In a balanced ecosystem, the amount of carbon used in photosynthesis and passed through the ecosystem is about the same as the amount given off in respiration and decomposition. This cycling of carbon between the atmosphere and organisms forms an organic pathway in the carbon cycle. Carbon can cycle quickly through this organic pathway, especially in aquatic ecosystems. In fact, during a given period of time, much more carbon is recycled through the organic pathway than through the geological pathway you will read about next.

Carbon in Rocks and Sediments

The geological pathway of the carbon cycle takes much longer than the organic pathway described above. In fact, it usually takes millions of years for carbon to cycle through the geological pathway. It involves processes such as rock formation, subduction, and volcanism.

As stated previously, most carbon in ocean water is in the form of bicarbonate ions. Bicarbonate ions may bind with other ions, such as calcium ions (Ca^{+}) or magnesium ions (Mg^{+}), and form insoluble compounds. Because the compounds are insoluble, they precipitate out of water and gradually form sedimentary rock, such as limestone (calcium carbonate, $CaCO_3$) or dolomite [calcium magnesium carbonate $CaMg(CO_3)_2$.

Dead organisms also settle to the bottom of the ocean. Many of them have shells containing calcium carbonate. Over millions of years, the pressure of additional layers of sediments gradually changes their calcium carbonate and other remaining organic compounds to carbon-containing sedimentary rock.

During some periods in Earth's history, very rich organic sediments were deposited. These deposits formed pockets of hydrocarbons. Hydrocarbons are organic compounds that contain only carbon and hydrogen. The hydrocarbons found in sediments are fossil fuels such as natural gas. The hydrocarbon methane is the chief component of natural gas.

Carbon-containing rocks and sediments on the ocean floor gradually move toward the edges of the ocean due to a process called seafloor spreading. The rocks eventually reach cracks in the crust, where they are pulled down into the mantle. This process, called **subduction**, occurs at subduction zones. In the mantle, the rocks melt and their carbon is stored. When volcanoes erupt, they return some of the stored carbon in the mantle to the atmosphere in the form of carbon dioxide, a process known as **volcanism**. This brings the geological pathway of the carbon cycle full circle.

Nitrogen Cycle

The atmosphere is the largest reservoir of nitrogen on Earth. It consists of 78 percent nitrogen gas (N_2). The **nitrogen cycle** moves nitrogen through abiotic and biotic components of ecosystems. **Figure** 15.16 shows how nitrogen cycles through a terrestrial ecosystem. Nitrogen passes from the atmosphere into soil. Then it moves through several different organisms before returning to the atmosphere to complete the cycle. In aquatic ecosystems, nitrogen passes through a similar cycle.

Absorption of Nitrogen

Plants and other producers use nitrogen to synthesize nitrogen-containing organic compounds. These include chlorophyll, proteins, and nucleic acids. Other organisms that

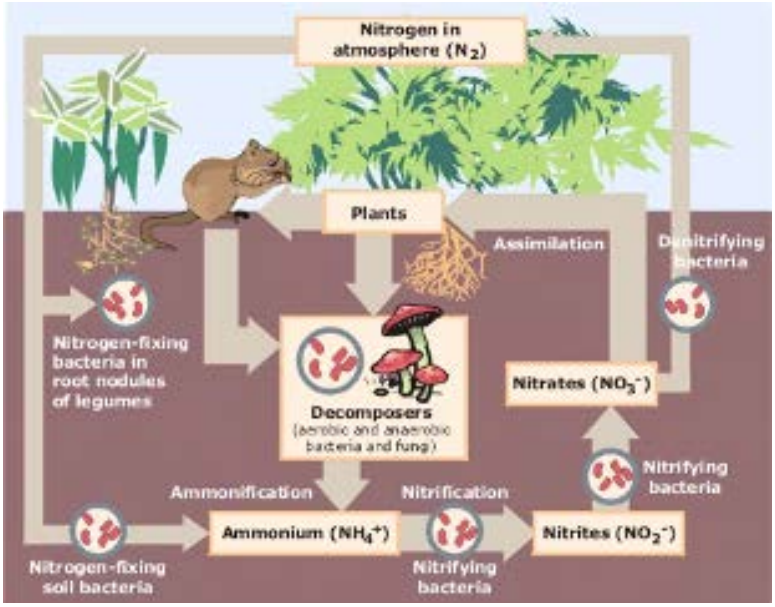

Figure 15.16: In a terrestrial ecosystem, the nitrogen cycle may include plants and consumers as well as several types of bacteria.

consume producers make use of the nitrogen in these organic compounds. Plants absorb substances such as nitrogen from the soil through their root hairs. However, they cannot absorb nitrogen gas directly. They can absorb nitrogen only in the form of nitrogen-containing ions, such as nitrate ions (NO_3^-).

Nitrogen Fixation

The process of converting nitrogen gas to nitrate ions that plants can absorb is called **nitrogen fixation**. It is carried out mainly by nitrogen-fixing bacteria, which secrete enzymes needed for the process. Some nitrogen-fixing bacteria live in soil. Others live in the root nodules of legumes such as peas and beans. In aquatic ecosystems, some cyanobacteria are nitrogen fixing. They convert nitrogen gas to nitrate ions that algae and other aquatic producers can use.

Nitrogen gas in the atmosphere can be converted to nitrates by several other means. One way is by the energy in lightning. Nitrogen is also converted to nitrates as a result of certain human activities. These include the production of fertilizers and explosives and the burning of fossil fuels. These human activities also create the gas nitrous oxide (N_2O). The concentration of this gas in the atmosphere has tripled over the past hundred years as a result. Nitrous oxide is a greenhouse gas that contributes to global warming and other environmental problems.

Ammonification and Nitrification

After being used by plants and animals, nitrogen is released back into the environment. When decomposers break down organic remains and wastes, they release nitrogen in the form of ammonium ions (NH_4^-). This is called **ammonification**. It occurs in both terrestrial and aquatic ecosystems. In terrestrial ecosystems, some nitrogen-fixing bacteria in soil and root nodules also convert nitrogen gas directly into ammonium ions.

Although some plants can absorb nitrogen in the form of ammonium ions, others cannot. In fact, ammonium ions may be toxic to some plants and other organisms. Certain soil bacteria, called nitrifying bacteria, convert ammonium ions to nitrites (NO_2^-). Other nitrifying bacteria convert the nitrites to nitrates, which plants can absorb. The process of converting ammonium ions to nitrites or nitrates is called **nitrification**.

Denitrification and the Anammox Reaction

Still other bacteria, called denitrifying bacteria, convert some of the nitrates in soil back into nitrogen gas in a process called **denitrification**. The process is the opposite of nitrogen fixation. Denitrification returns nitrogen gas back to the atmosphere, where it can continue the nitrogen cycle.

In the ocean, another reaction occurs to cycle nitrogen back to nitrogen gas in the atmosphere. The reaction, called the **anammox reaction**, is enabled by certain bacteria in the water. In the reaction, ammonium and nitrite ions combine to form water and nitrogen gas. This is shown by the equation:

$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$.

The anammox reaction may contribute up to half of the nitrogen gas released into the atmosphere by the ocean. The reaction may also significantly limit production in ocean ecosystems by removing nitrogen compounds that are needed by aquatic producers and other organisms.

Lesson Summary

- Biogeochemical cycles are closed loops through which chemical elements or water move through ecosystems. Examples of biogeochemical cycles include the water cycle, carbon cycle, and nitrogen cycle.
- The water cycle recycles water through ecosystems. Processes by which water changes state in the water cycle include evaporation, sublimation, transpiration, and condensation.
- The organic pathway of the carbon cycle moves carbon from the atmosphere, through producers and other organisms in ecosystems, and back to the atmosphere. The geo-

logical pathway moves carbon from the atmosphere, through the ocean to rocks and the mantle, and back to the atmosphere.
- The nitrogen cycle moves nitrogen gas from the atmosphere into soil or water, where nitrogen-fixing bacteria convert it to a form that producers can use. Nitrifying bacteria help nitrogen cycle through ecosystems. Denitrifying bacteria return nitrogen gas back to the atmosphere. The anammox reaction returns nitrogen back to the atmosphere from ocean water.

Review Questions

1. What is a biogeochemical cycle? Name one example.
2. Identify and define two processes by which water changes state in the water cycle.
3. State three ways that carbon dioxide enters Earth's atmosphere.
4. How do bacteria convert nitrogen gas to a form that producers can use?
5. Describe all the ways that a single tree might be involved in the carbon cycle.
6. Explain why growing a crop of legumes can improve the ability of the soil to support the growth of other plants.
7. Compare and contrast organic and geological pathways in the carbon cycle.
8. Identify an exchange pool and a reservoir in the water cycle. Explain your choices.

Further Reading / Supplemental Links

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Vocabulary

ammonification The release of nitrogen in the form of ammonium ions (NH_4^-) due to the break down of organic remains and wastes by decomposers.

anammox reaction Reaction in which ammonium and nitrite ions combine to form water and nitrogen gas; enabled by certain bacteria in the water.

aquifer An underground layer of water-bearing, permeable rock.

biogeochemical cycle A closed loop through which a chemical element or water moves through ecosystems.

carbon cycle Pathways of exchange that interconnect the four major reservoirs of carbon: the ocean, the atmosphere, the biosphere and organic sediments, such as fossil fuels.

cellular respiration The process by which cells oxidize glucose and produce carbon dioxide, water, and energy.

denitrification The conversion of some of the nitrates in soil back into nitrogen gas; done by denitrifying bacteria; returns nitrogen gas back to the atmosphere, where it can continue the nitrogen cycle.

groundwater Water that infiltrates the ground.

infiltration Rain that falls on land and soaks into the ground.

nitrification The process of converting ammonium ions to nitrites or nitrates.

nitrogen cycle The cycle that moves nitrogen through abiotic and biotic components of ecosystems.

nitrogen fixation The process of converting nitrogen gas to nitrate ions that plants can absorb; carried out mainly by nitrogen-fixing bacteria.

precipitation Forms when water droplets in clouds become large enough to fall.

runoff Rain that falls on land and flows over the land.

subduction A process where carbon containing rocks and sediments on the ocean floor are pulled down into the mantle; due to seafloor spreading.

sublimation The transformation of snow and ice directly into water vapor; occurs as the snow and ice are heated by the sun.

transpiration A process by which plants lose water; occurs when stomata in leaves open to take in carbon dioxide for photosynthesis and lose water to the atmosphere in the process.

volcanism The process of returning some of the stored carbon in the mantle to the atmosphere in the form of carbon dioxide; occurs when volcanoes erupt.

water cycle Describes the continuous movement of water molecules on, above, and below Earth's surface.

Points to Consider

Matter is recycled through abiotic and biotic components of all ecosystems. However, ecosystems vary in the amount of matter they recycle. For example, forests recycle more matter than deserts.

- What factors do you think might cause ecosystems to differ in this way?
- What abiotic components of the environment do you think might be important?
- What about the amount of sunlight or precipitation that ecosystems receive?
- What roles do you think these abiotic components play in cycles of matter?

Image Sources

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Chapter 16

Biomes, Ecosystems, and Communities

16.1 Lesson 16.1: Biomes

Lesson Objectives

- Define biome and climate, and explain how biomes are related to climate.
- Outline how climate determines growing conditions for plants and affects the number and biodiversity of plants in a biome.
- Explain how climate is related to biodiversity of biomes and adaptations of organisms.

Introduction

If you look at the two pictures in **Figure 1** below, you will see very few similarities. The picture on the left shows a desert in Africa. The picture on the right shows a rainforest in Australia. What is the most obvious difference between the two places? It could be that the desert does not have any visible plants, whereas the rainforest is densely packed with trees. What causes these two places to be so different? The main reason is climate.

Biomes and Climate

The two pictures above represent two different types of biomes: deserts and rainforests. A **biome** is a group of similar ecosystems that cover a broad area. Biomes are major subdivisions of the biosphere. They can be classified into two major types:

- **Terrestrial biomes**: biomes on land

Figure 16.1: Sahara Desert in northern Africa (left). Rainforest in northeastern Australia (right).

- **Aquatic biomes**: biomes in water

You will read about terrestrial biomes in Lesson 16.2 and aquatic biomes in Lesson 16.3. First, however, it is important to understand how climate influences biomes. Climate is the most important abiotic (non-living) factor affecting the distribution of terrestrial biomes of different types. Climate determines the growing conditions in an area, so it also determines what plants can grow there. Animals depend directly or indirectly on plants, so the type of animals that live in an area also depends on climate.

What Is Climate?

Climate is the average weather in an area over a long period of time, whereas weather is a day to day explanation. Weather and climate are described in terms of factors such as temperature and precipitation. The climate of a particular location depends, in turn, on its latitude (distance from the equator) and altitude (distance above sea level). Other factors that affect an area's climate include its location relative to the ocean or mountain ranges. Temperature and moisture are the two climatic factors that most affect terrestrial biomes.

Temperature

In general, temperature on Earth's surface falls from the equator to the poles. Based on temperature, climates can be classified as tropical, temperate, or arctic, as shown in **Figure 2**. Temperature also falls from lower to higher altitudes, for example, from the base of a mountain to its peak. This explains why the tops of high mountains in tropical climates may be snow-capped year-round.

The ocean may also play an important role in the temperature of an area. Coastal areas may have milder climates than areas farther inland at the same latitude. This is because the temperature of the ocean changes relatively little from season to season, and this affects the

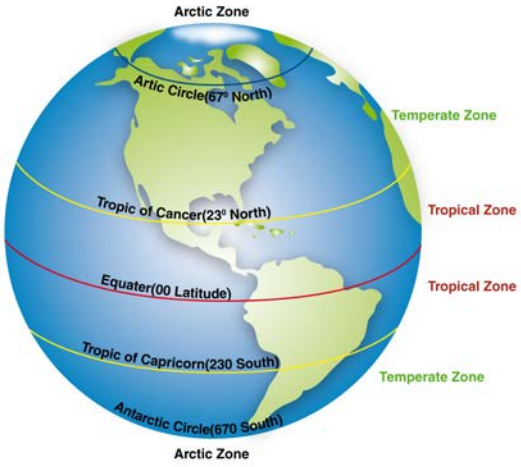

Figure 16.2: Major climate zones based on temperature include tropical, temperate, and arctic zones. The tropical zone extends from the Tropic of Capricorn to the Tropic of Cancer. The two temperate zones extend from the tropical zone to the arctic or antarctic circle. The two arctic zones extend from the arctic or antarctic circle to the north or south pole.

temperature on nearby coasts. As a result, many coastal areas have both warmer winters and cooler summers than inland areas.

Moisture

Based on the amount of water available to plants, climates can be classified as arid (dry), semi-arid, semi-humid, or humid (wet). The moisture of a biome is determined by both precipitation and evaporation. Evaporation, in turn, depends on heat from the sun. Worldwide precipitation patterns result from global movements of air masses and winds, which are shown in **Figure 3**. For example, warm, humid air masses rise over the equator and are moved north and south by global air currents. The air masses cool and cannot hold as much water. As a result, they drop their moisture as precipitation. This explains why many tropical areas receive more precipitation than other areas of the world.

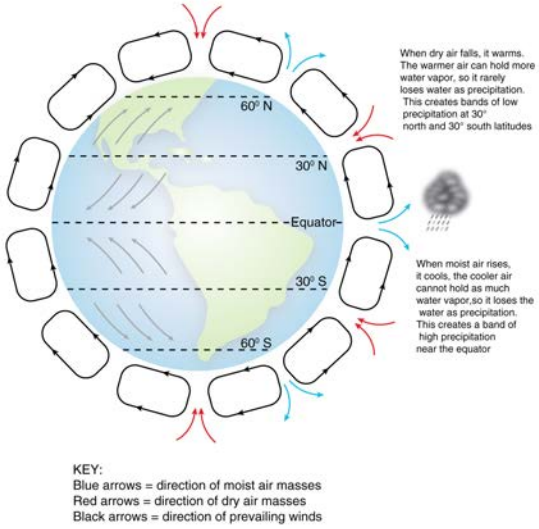

Figure 16.3: This model of Earth shows the direction in which air masses typically move and winds usually blow at different latitudes. These movements explain why some latitudes receive more precipitation than others.

When the same air masses descend at about 30° north or south latitude (see **Figure 3**), they are much drier. This explains why dry climates are found at these latitudes. These latitudes are also warm and sunny, which increases evaporation and dryness. Dry climates are found near the poles, as well. Extremely cold air can hold very little moisture, so precipitation

is low in arctic zones. However, these climates also have little evaporation because of the extreme cold. As a result, cold climates with low precipitation may not be as dry as warm climates with the same amount of precipitation.

Distance from the ocean and mountain ranges also influences precipitation. For example, one side of a mountain range near the ocean may receive a lot of precipitation because warm, moist air masses regularly move in from the water. As air masses begin to rise up over the mountain range, they cool and drop their moisture as precipitation. This is illustrated in **Figure 4**.

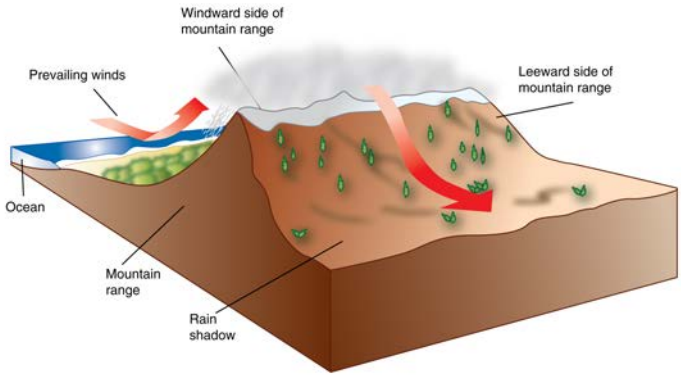

Figure 16.4: The windward side of this mountain range has a humid climate, whereas the leeward side has an arid climate. On the windward side, warm moist air comes in from the ocean, rises and cools, and drops its moisture as rain or snow. On the leeward side, the cool dry air falls, warms, and picks up moisture from the land. How has this affected plant growth on the two sides of the mountain range?

By the time the air masses reach the other side of the mountain range, they no longer contain moisture. As a result, land on this side of the mountain range receives little precipitation. This land is in the **rain shadow** of the mountain range. Many inland areas far away from the ocean or mountain ranges are also dry. Air masses that have passed over a wide expanse of land to reach the interior of a continent usually no longer carry much moisture.

Climate and Plant Growth

Plants are the major producers in terrestrial biomes. Almost all other terrestrial organisms depend on them either directly or indirectly for food. Plants need air, warmth, sunlight,

water, and nutrients to grow. Climate is the major factor affecting the number and diversity of plants that can grow in a terrestrial biome. Climate determines the average temperature and precipitation, the length of the growing season, and the quality of the soil, including levels of soil nutrients.

Growing Season

The **growing season** is the period of time each year when it is warm enough for plants to grow. The timing and length of the growing season determine what types of plants can grow in an area. For example, near the poles the growing season is very short. The temperature may rise above freezing for only a couple of months each year. Because of the cold temperatures and short growing season, trees and other slow-growing plants are unable to survive. The growing season gets longer from the poles to the equator. Near the equator, plants can grow year-round if they have enough moisture. A huge diversity of plants can grow in hot, wet climates.

The timing of precipitation also affects the growing season. In some areas, most of the precipitation falls during a single wet season (such as in California), rather than throughout the year (such as in New England). In these areas, the growing season lasts only as long as there is enough moisture for plants to grow.

Soil

Plants need soil that contains adequate nutrients and organic matter. Nutrients and organic matter are added to soil when plant litter and dead organisms decompose. In cold climates, decomposition occurs very slowly. As a result, soil in cold climates is thin and poor in nutrients. Soil is also thin and poor in hot, wet climates because the heat and humidity cause such rapid decomposition that little organic matter accumulates in the soil. The frequent rains also leach nutrients from the soil. Thin, poor soil is shown in the left drawing of **Figure 5**. The right drawing shows thick, rich soil. This type of soil is generally found in temperate climates and is best for most plants.

Biome Biodiversity and Adaptations

Because plants are the most important producers in terrestrial biomes, anything that affects their growth also influences the number and variety of other organisms that can be supported in a biome. Therefore, climate has a major impact on the biodiversity of biomes.

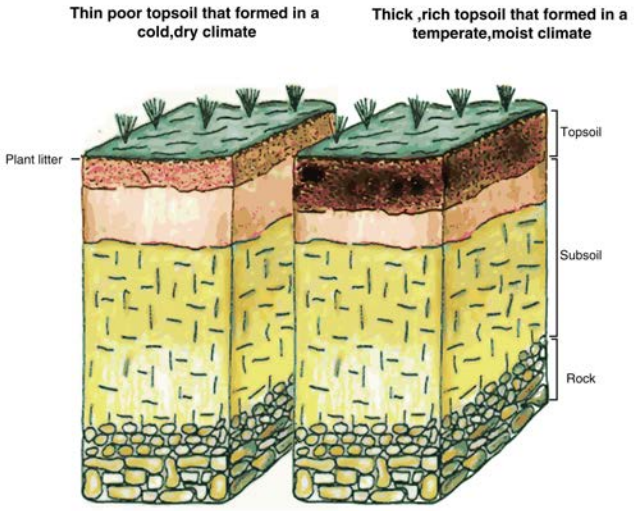

Figure 16.5: The soil on the left has a thin layer of topsoil, the part of soil where most plant roots obtain moisture and nutrients. The topsoil is light in color, which means that it is poor in nutrients and organic matter. The soil on the right has a thicker layer of topsoil. Its dark color indicates that the topsoil is rich in nutrients and organic matter.

Biodiversity

Biodiversity refers to the number of different species of organisms in a biome (or ecosystem or other ecological unit). Biodiversity is usually greater in warmer biomes. Therefore, biodiversity generally decreases from the equator to the poles. Biodiversity is usually greater in wetter biomes, as well. Remember the desert and rainforest pictured in **Figure 1**? The biodiversity of these two biomes is vastly different. Both biomes have warm climates, but the desert is very dry, and the rainforest is very wet. The desert has very few organisms, so it has low biodiversity. Some parts of the desert may have no organisms, and therefore zero biodiversity. In contrast, the rainforest has the highest biodiversity of any biome on Earth.

Adaptations

Plants, animals, and other organisms evolve adaptations to suit them to the abiotic factors in their biome. Abiotic factors to which they adapt include temperature, moisture, growing season, and soil. This is why the same type of biome in different parts of the world has organisms with similar adaptations. For example, biomes with dry climates worldwide have plants with similar adaptations to aridity, such as special tissues for storing water (see **Figure 6**).

Figure 16.6: (left) The large hollow leaves of an African aloe plant store water and help the plant survive in its arid biome. (right) Cacti like these are found in arid biomes of North America. They store water in their thick, barrel-like stems.

In biomes with a severe cold or dry season, plants may become dormant during that season of the year. In dormant plants, cellular activities temporarily slow down, so the plants need less sunlight and water. For example, many trees shed their leaves and become dormant

during very cold or dry seasons. Animals in very cold or dry biomes also must adapt to these abiotic factors. For example, adaptations to cold include fur or fat, which insulates the body and helps retain body heat.

Lesson Summary

- A biome is a group of similar ecosystems that cover a broad area. Climate is the average weather in an area over a long period of time. Climate is the most important abiotic factor affecting the distribution of terrestrial biomes.
- Climate includes temperature and precipitation, and it determines growing season and soil quality. It is the major factor affecting the number and diversity of plants in terrestrial biomes.
- By affecting plants, which are the main producers, climate affects the biodiversity of terrestrial biomes. Plants and other organisms also evolve adaptations to climatic factors in their biomes, including adaptations to extreme cold and dryness.

Review Questions

1. Name three factors that help determine the climate of an ecosystem.
2. What is a rain shadow?
3. List some important factors related to climate that plants need in order to grow?
4. Compare the data for Seattle and Denver in the table below. What factors might explain why Seattle is warmer in the winter than Denver, even though Seattle is farther north?:

Table 16.1:

City	Latitude	Altitude	Location	Temperature[1]
Seattle, Washington	48°N	429 ft	Coastal	33°F
Denver, Colorado	41°N	5,183 ft	Interior	15°F

5.
6. [1]
7. Average low temperature in January
8. Explain how the quality of soil in an area is influenced by climate.
9. Why is biodiversity higher at the equator than it is near the poles?

Further Reading / Supplemental Links

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- Susan L. Woodward, Biomes of Earth: Terrestrial, Aquatic, and Human-Dominated. Greenwood Press, 2003.
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- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/B/Biomes.html

Vocabulary

aquatic biome Biome in water.

biodiversity Number of different species of organisms in a biome (or ecosystem or other unit).

biome Group of similar ecosystems that cover a broad area.

climate Average weather in an area over a long period of time.

growing season Period of time each year when it is warm enough for plants to grow.

rain shadow Land on the leeward side of a mountain range that receives very little precipitation.

terrestrial biome Biome on land.

Points to Consider

Plants and the other organisms in terrestrial biomes are greatly influenced by climate.

- What is the climate like where you live?
- How hot or cold does it get, and how much precipitation usually falls?
- Discuss with your class the climate in your area and how it seems to affect plant growth.
- What plants and animals are naturally found in your part of the country?

16.2 Lesson 16.2: Terrestrial Biomes

Lesson Objectives

- State how terrestrial biomes are classified and distributed around the globe.
- Outline abiotic and biotic factors in tundra and boreal forest biomes.
- Describe climatic factors and organisms of temperate zone biomes.
- List abiotic factors in deserts and adaptations of desert organisms.
- Identify abiotic factors and organisms in tropical biomes.

Introduction

Terrestrial biomes include all land areas on Earth where organisms live. The major biomes cover large regions and are found on more than one continent. They are generally classified on the basis of climatic factors and the types of plants that are the primary producers.

Classification of Terrestrial Biomes

Scientists have created several different systems for classifying terrestrial biomes. Biomes in most classification systems include tundra, boreal forest, temperate forest, temperate grassland, chaparral, tropical forest, tropical grassland, and desert. The worldwide distribution of these biomes is shown in **Figure 1**.

The distribution of biomes shown in **Figure 1** reflects global patterns of temperature and moisture. It also reflects conditions in earlier times. Many areas have been disturbed by human actions, some more so than others. For example, most tundra biomes have been changed very little by human actions, but many forests have been completely cleared. Some biomes, including tropical rainforests, cannot be replaced once they have been destroyed. **Figure 2** summarizes important features of most of the biomes shown in **Figure 1**. Refer to both figures as you read about these terrestrial biomes throughout this lesson.

Arctic and Subarctic Biomes

Artic and subarctic biomes are found near the north and south poles or at high altitudes in other climate zones. The biomes include tundra and boreal forests. Both have cold, dry climates and poor soil. They can support only limited plant growth and have low biodiversity.

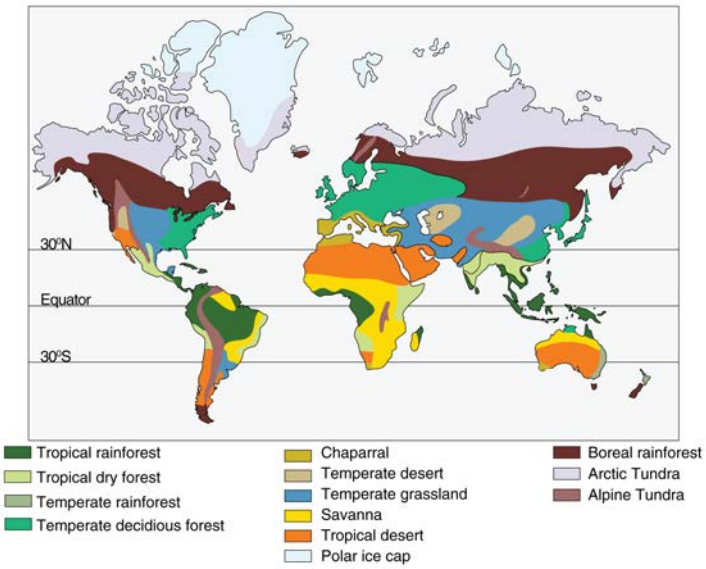

Figure 16.7: Distribution of Earth's major terrestrial biomes.

Tundra

Tundra is an arctic biome where it is too cold for trees to grow. Outside of the polar ice caps, tundra has the coldest temperatures on Earth. There are two types of tundra: arctic tundra, which is also found in Antarctica, and alpine tundra, which is found only at high altitudes.

- **Arctic tundra** occurs north of the arctic circle and south of the antarctic circle. It covers much of Alaska and vast areas of northern Canada and Russia. It is also found along the northern coast of Antarctica.
- **Alpine tundra** occurs in mountains around the world at any latitude, but only above the tree line. The **tree line** is the edge of the zone at which trees are able to survive. Alpine tundra is found in the Rocky Mountains in the United States and in several other mountain ranges around the world.

Both types of tundra receive very low precipitation, but little of it evaporates because of the cold. Arctic tundra has **permafrost,** which is soil that is frozen year-round. The top layer of soil thaws in the summer, but deeper layers do not. As a result, water cannot soak into the ground. This leaves the soil soggy and creates many bogs, lakes, and streams. Alpine tundra does not have permafrost, except at very high altitudes. Therefore, alpine tundra soil tends to be dry rather than soggy.

Biome: Other Name(s)	Type of Climate, Growing Season, Soil Quality	Biodiversity, Common Plants, Common Animals
Tundra: Artic tundra (high latitudes) Alpine tundra (high altitudes)	*Type of climate*: arctic, arid *Growing season:* very short *Soil quality:* Very poor	 Alpine tundra in the Alps Mountains of Switzerland in Europe  Arctic tundra on the northern coast of Alaska in the United States *Biodiversity:* very low *Plants*: mosses, grasses, and lichens; few herbaceous plants; no trees *Animals:* insects; birds (summer only); no amphibians or reptiles; mammals such as rodents, arctic hares, arctic foxes, polar bears; caribou (summer only); mountain goats and chinchillas (alpine tundra only)
Boreal Forest: Taiga Northern conifer forest	*Climate:* subarctic, semi-arid *Growing season:* short *Soil quality:* Poor	*Biodiversity*: low *Plants:* conifers such as cedar, spruce, pine, and fir; mosses and lichens *Animals:* insects; birds (mainly in summer); no amphibians or reptiles; mammals such as rodents, rabbits, minks, raccoons, bears, and moose; caribou (winter only)  Boreal forest in central (inland) Alaska, United States
Temperate Deciduous Forest: Temperate hardwood forest Temperate broadleaf forest	*Climate:* temperate, semi-humid *Growing season:* medium *Soil quality:* good *Climate:* temperate, semi-arid *Growing season:* medium *Soil quality:* excellent	 Temperate deciduous forest in Pennsylvania, eastern United States *Biodiversity*: high *Plants*: broadleaf deciduous trees such as beech, maple, oak, and hickory; ferns, mosses, and shrubs; many herbaceous plants *Animals*: insects, amphibians, reptiles, and birds; mammals such as mice, chipmunks, squirrels, raccoons, foxes, deer, black bears, bobcats, and wolves  Temperate grassland in Nebraska, midwestern United States *Biodiversity*: medium–high *Plants*: grasses; other herbaceous plants; no trees *Animals*: invertebrates such as worms and insects; amphibians, reptiles, and birds; mammals such as mice, prairie dogs, rabbits, foxes, wolves, coyotes, bison, and antelope; kangaroo (only in Australia)
Chaparral Mediterranean scrub forest	*Climate:* temperate, semi-arid *Growing season:* medium *Soil quality:* poor	*Biodiversity*: low–medium *Plants:* shrubs and small trees such as scrub oak and scrub pine *Animals:* insects, reptiles, and birds; mammals such as rodents and deer  Chaparral in southern California, United States
Desert	*Climate:* temperate or tropical, arid *Growing season:* varies *Soil quality:* very poor	*Biodiversity*: none–low *Plants:* plants adapted to dryness, such as cacti, sagebrush, and mesquite; virtually no plants if extremely arid *Animals*: insects, reptiles, and birds; mammals such as rodents and coyotes  Desert in southern California, United States
Tropical Rainforest	*Climate:* tropical, humid *Growing season:* year-round *Soil quality:* excellent	*Biodiversity*: very high *Plants*: tall flowering, broadleaf evergreen trees; vines and epiphytes; few plants on forest floor *Animals:* insects, amphibians, reptiles, and birds; mammals such as monkeys, sloths, leopards, jaguars, pigs, and tigers  Tropical rainforest in Ecuador, South America
Tropical Grassland Savanna	*Climate*: tropical, semi-arid *Growing season:* year-round *Soil quality:* poor	*Biodiversity*: low–medium *Plants*: grasses; scattered clumps of trees *Animals*: insects, reptiles, and birds; mammals such as zebras, giraffes, antelopes, lions, cheetahs, and hyenas  Elephant browsing on the leaves of an acacia tree in savanna in Kenya, eastern Africa

Figure 16.8: These biomes are described more fully in the text. Refer to to see where each biome is found.

Global warming poses a serious threat to Arctic tundra biomes because it is causing the permafrost to melt. When permafrost melts, it not only changes the tundra. It also releases large amounts of methane and carbon dioxide into the atmosphere. Both are greenhouse gases, which contribute to greater global warming.

The most common vegetation in tundra is mosses and lichens. They can grow in very little soil and become dormant during the winter. Tundra is too cold for amphibians or reptiles, which cannot regulate their own body heat. Insects such as mosquitoes can survive the winter as pupae and are very numerous in summer. In addition, many species of birds and large herds of caribou migrate to arctic tundra each summer. However, few birds and mammals live there year-round. Those that remain have adapted to the extreme cold. Polar bears are an example. They have very thick fur to insulate them from the cold. In alpine tundra, animals must adapt to rugged terrain as well as to cold. Alpine animals include mountain goats, which not only have wool to keep them warm but are also sure-footed and agile.

Boreal Forests

A **boreal forest** is a subarctic biome covered with conifers. Conifers are cone-bearing, needle-leaved evergreen trees such as spruces. Boreal forests are found only in the northern hemisphere. They occur just south of the arctic circle in Alaska, Canada, northern Europe, and Russia (where they are called taiga). They also occur in extreme northern regions of Minnesota, New York State, New Hampshire, and Maine.

Boreal forests have harsh continental climates, with very cold winters and relatively warm summers. The growing season is also short. Precipitation is quite low, but there is little evaporation. Most of the precipitation falls in the summer when plants are growing, so there is enough moisture for dense plant growth. A thick carpet of evergreen needles on the forest floor causes the soil to be too acidic for most other plants.

Conifers have adapted to the difficult conditions in several ways. They have shallow roots that suit them for the thin soil. They have needles instead of leaves, which reduce water loss during the long, dry winters. The needles are also very dark green in color, which maximizes absorption of sunlight for photosynthesis. Although boreal forests are dense with conifers, there are only a few different species of trees. Vegetation on the forest floor consists mostly of mosses and lichens. Animals found in boreal forests include insects, birds, and mammals such as rabbits, foxes, and brown bears. Caribou also spend their winters there. Like tundra, the boreal forest is too cold for amphibians or reptiles.

Temperate Biomes

Temperate biomes cover most of the continental United States and Europe. They also cover large parts of Asia. Types of temperate biomes include forests, grasslands, and chaparral.

Temperate Forests

There are two types of temperate forests: temperate deciduous forests and temperate rainforests. Both types have a temperate climate and good soil. A temperate climate is a moderate climate that is neither extremely hot nor extremely cold. A temperate climate can be either continental or coastal. Continental temperate climates are found inland, and they tend to have cold winters, hot summers, and moderate precipitation. Coastal temperate climates are found near the ocean, and they tend to have mild winters, cool summers, and high precipitation.

- **Temperate deciduous forests** are found in areas with continental temperate climates, such as the eastern United States and Canada and throughout much of Europe. These forests consist mainly of deciduous trees, such as maples and oaks, which lose their leaves in the fall. There are many other species of plants as well. Animals include insects, amphibians, reptiles, and birds. Mammals are also common, including rabbits and wolves.
- **Temperate rainforests** are found in areas with coastal temperate climates, such as the northwestern coast of North America and certain coastal regions of other continents. These forests consist mainly of evergreen trees, such as hemlocks and firs. Mosses, lichens, and ferns grow on the forest floor. There are also many epiphytic plants. Animals include insects, amphibians, reptiles, and birds. There are also many mammals, such as squirrels and deer.

Epiphytes are plants that grow on other plants. They use the other plants for support, not nutrients, and generally do not harm the plants they grow on. They grow high in the branches of trees where there is more sunlight available for photosynthesis.

Temperate Grasslands

Temperate grasslands are temperate biomes that consist mainly of grasses. They are found in the midwestern region of North America and in inland areas of most other continents. The climate is continental, and precipitation is relatively low. However, the majority of the precipitation falls during the growing season when plants need it the most.

Biomes are often referred to by local names. For example, a temperate grassland biome is known as prairie in North America, outback in Australia, pampa in South America, and steppe in central Asia. Can you find each of these temperate grasslands on the map in **Figure 1**?

The soil of temperate grasslands is the richest, deepest soil on Earth. It is densely covered with thick grasses that decompose to add large amounts of organic matter and nutrients to the soil. Grasses also have thick mats of roots that hold the soil in place and prevent erosion. The low rainfall does not leach many nutrients from the soil, but it does lead to frequent

fires. The fires help prevent woody vegetation from moving in if a grassland is disturbed. This is because grasses can grow back after a fire, whereas most woody plants cannot.

The rich, deep soil supports high productivity. This is why the temperate grassland of the US midwest is known as the *Breadbasket of America.* Grass plants are closely spaced and can support many herbivore consumers. These range from grasshoppers to deer. Many worms and other invertebrates (animals without a backbone) consume organic matter in the soil. Grassland animals also include carnivores such as foxes and coyotes.

Chaparral

Chaparral is a shrub forest biome dominated by densely-growing evergreen shrubs or small trees, such as scrub oak. There are few other species of plants. Chaparral is found mainly in central and southern California and around the Mediterranean Sea. The climate, called a Mediterranean climate, has mild wet winters and hot dry summers. Fires are frequent because of the summer dryness, and the soil is relatively poor.

The majority of chaparral trees and plants are adapted to the dry summers. For example:

- Trees are short, which reduces their need for water.
- Many plants are dormant during the dry season, which also reduces water needs.
- The leaves of some plants have waxy coatings, which reduce water loss.

Most chaparral plants are adapted to frequent fires, as well. For example:

- Many plants can grow back quickly from the roots after burning to the ground.
- Some plants produce seeds that need fire in order to germinate.
- Many plants have thick underground stems that can survive fires.

The densely growing trees make it difficult for very large animals to penetrate the chaparral, so most chaparral animals are small. They include insects, birds, reptiles, and rodents. The largest animals are deer, which browse on the leaves of chaparral trees.

Deserts

A **desert** is a biome that receives no more than 25 centimeters (10 inches) of precipitation per year. Deserts are found in both temperate and tropical areas. The largest deserts are found at about 30° north or south latitude due to the dry air masses over these latitudes. Deserts also occur in rain shadows. A rain shadow is a dry region on the leeward side of a mountain range (see Lesson 16.1). Examples of rain shadow deserts include Death Valley and the Mojave Desert, both partly in California. The dry air in deserts leads to extreme

temperature variations from day to night. Without water vapor in the air, there are no clouds to block sunlight during the day or hold in heat at night.

Desert soil is usually very poor. They tend to be sandy or rocky and lack organic content. Because of the low precipitation, minerals are not leached out and may become too concentrated for plants to tolerate. Plant cover is very sparse, so most of the soil is exposed and easily eroded by wind. The occasional rain tends to be brief but heavy, causing runoff and more erosion.

Most desert plants have evolved adaptations to the extreme dryness. For example:

- Many plants have special water-storing tissues in leaves, stems, or roots.
- Some plants have very long taproots that can reach down to the water table.
- Some plants have wide-spreading roots that can absorb water over a large area.
- Plants may have small, spiny leaves that help reduce water loss.

Most desert animals have adaptations to the extreme heat and bright sunlight. For example:

- Many small animals stay underground in burrows during the day and come out only at night.
- Most animals that are active in daytime spend as much time as possible in the shade of rocks or plants.
- Some animals have very large ears or other appendages, which help them lose heat to the environment, keeping them cooler.
- Many animals are light in color, which helps them reflect sunlight and stay cooler.

Tropical Biomes

Tropical biomes receive more sunlight than any other biomes on Earth. They also have high temperatures year-round. In addition to deserts, tropical biomes include forests and grasslands.

Tropical Forests

There are two types of tropical forests: tropical rainforests and tropical dry forests. Both occur near the equator, so they have plenty of sunlight and warmth year-round. However, they differ in the amount and timing of the precipitation they receive.

- **Tropical rainforests** receive more precipitation than any other biome. They are found near the equator in Central and South America and Africa. The soil is thin and poor, partly because the lush plant growth uses up nutrients before they can

accumulate in the soil. Biodiversity of animals as well as plants is greater than in all other biomes combined. Most plants are tall, broadleaf evergreen trees. They form a dense canopy over the forest, so little sunlight reaches the forest floor. The many vines and epiphytes reach sunlight by growing on trees. Numerous animal species also live in trees, including monkeys, sloths, and leopards.

- **Tropical dry forests** occur in tropical areas where most of the precipitation falls during a single wet season. As a result, there is a pronounced dry season. Tropical dry forests are found in parts of Central and South America, Africa, and India. Trees and other plants are widely spaced because there is not enough water for denser growth. The plants also have adaptations to help them cope with seasonal drought. For example, many go dormant during the dry season, which reduces their need for water. Animals that live in tropical dry forests include arboreal animals such as monkeys and ground-dwelling animals such as rodents.

Tropical Grasslands

Tropical grasslands are tropical biomes with relatively low rainfall where the primary producers are grasses. Tropical grasslands are found mainly in Africa, where they are called savannas. They have high temperatures year-round, but relatively low precipitation. Moreover, most of the precipitation falls during a single wet season, leaving the rest of the year very dry. The soil is also poor.

In addition to grasses, there are scattered clumps of trees in most tropical grasslands. The trees are drought-adapted species such as acacia, which have narrow leaves that reduce water loss. Acacia trees also have thorns that discourage browsing by herbivores. Africa savannas are well known for their huge herds of herbivores, including zebra, giraffe, and wildebeest. They are also well known for their large carnivores—such as lions, cheetahs, and hyenas—that prey on the herbivores.

Lesson Summary

The concept map below shows how the terrestrial biomes described in this lesson are related.

Review Questions

1. Identify the two types of tundra and where they are found.
2. Name two temperate biomes and the main type of plant found in each biome.
3. In which biome are you most likely to find grasses, zebras, and lions?
4. Assume a new species of lizard has been discovered in the northern hemisphere. It lives in an area of dense evergreen forest, where mosses and lichens grow on the forest floor. Identify the biome in which the lizard was found and explain your answer.

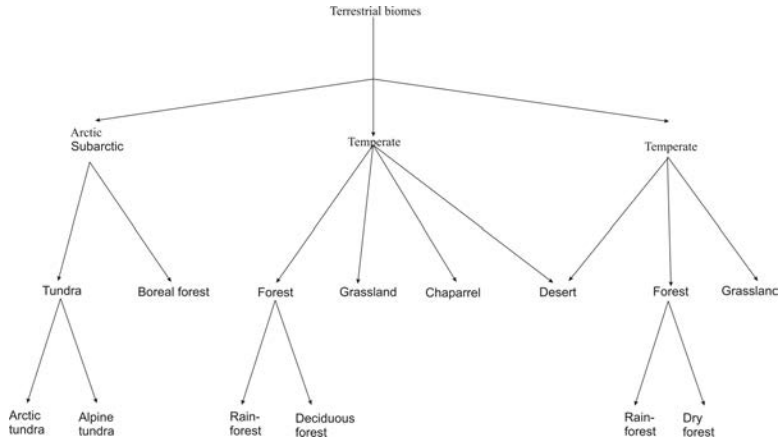

Figure 16.9

5. If you were to design a well-adapted desert animal, what traits would you give it to help it survive in its desert environment?
6. Compare and contrast two types of temperate forests.
7. If the tropics receive more sunlight year-round than any other biome, why are some plants in tropical rainforests adapted to low levels of sunlight?

Further Reading / Supplemental Links

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Vocabulary

alpine tundra Tundra biome that occurs in mountains around the world at any latitude, but only above the tree line.

arctic tundra Tundra biome that occurs north of the arctic circle and south of the antarctic circle.

boreal forest Subarctic biome covered with conifers.

chaparral Temperate biome with a Mediterranean climate that consists mainly of densely-growing evergreen shrubs such as scrub oak.

desert Temperate or tropical biome that receives no more than 25 centimeters of precipitation per year.

epiphyte Type of plant that grows on other plants for support.

permafrost Frozen soil year-round.

temperate deciduous forest Temperate biome that receives moderate rainfall and consists mainly of deciduous trees such as maples.

temperate grassland Temperate biome that receives relatively low precipitation and consists mainly of grasses.

temperate rainforest Temperate biome that receives heavy rainfall and consists mainly of evergreen trees such as hemlocks.

tree line Edge of the zone at which trees are able to survive.

tropical dry forest Tropical biome that receives relatively low rainfall, has a dry season, and consists mainly of widely spaced, drought-adapted trees.

tropical grassland Tropical biome that receives relatively low rainfall, has a dry season, and consists mainly of grasses.

tropical rainforest Tropical biome that receives heavy rainfall and consists mainly of tall, broadleaf evergreen trees.

tundra Arctic biome where it is too cold for trees to grow.

Points to Consider

The land areas where terrestrial biomes are found cover only 30 percent of Earth's surface. The rest of the surface is covered by water.

- What types of biomes do you think occur in water?
- How do you think water biomes might be classified?
- What do you think are some of the organisms that live in water biomes?

16.3 Lesson 16.3: Aquatic Biomes

Lesson Objectives

- Describe how aquatic biomes are divided into zones, and list types of aquatic organisms.
- Identify marine biomes, and state which biomes have the highest biodiversity.
- Name types of freshwater biomes, and describe how they differ from one another.

Introduction

Terrestrial organisms are generally limited by temperature and moisture. Therefore, terrestrial biomes are defined in terms of these abiotic factors. In contrast, most organisms that live in the water do not have to deal with extremes of temperature or moisture. Instead, their main limiting factors are the availability of sunlight and the concentration of dissolved nutrients in the water.

What Are Aquatic Biomes?

Aquatic biomes are biomes found in water. Water covers 70 percent of Earth's surface, so aquatic biomes are a major component of the biosphere. However, they have less total biomass than terrestrial biomes. Aquatic biomes can occur in either salt water or freshwater. About 98 percent of Earth's water is salty, and only 2 percent is fresh. The primary saltwater biome is the ocean. Major freshwater biomes include lakes and rivers.

Aquatic Zones

In large bodies of standing water (including the ocean and lakes), the water can be divided into zones based on the amount of sunlight it receives. There is enough sunlight for photosynthesis only in - at most - the top 200 meters of water. Water down to this depth is called the **photic zone**. Deeper water, where too little sunlight penetrates for photosynthesis, is called the **aphotic zone.**

Surface water dissolves oxygen from the air, so there is generally plenty of oxygen in the photic zone to support organisms. Water near shore usually contains more dissolved nutrients than water farther from the shore. This is because most dissolved nutrients enter a body of water from land, carried by runoff or rivers that empty into the body of water. When aquatic organisms die, they sink to the bottom, where decomposers release the nutrients they contain. As a result, deep water may contain more nutrients than surface water.

`Deep ocean water may be forced to the surface by currents in a process called '''upwelling.''' When this happens, dissolved nutrients are brought to the surface from the deep ocean. The nutrients can support large populations of producers and consumers, including many species of fish. As a result, areas of upwelling are important for commercial fishing.`With these variations in sunlight, oxygen, and nutrients, different parts of the ocean or a lake have different types and numbers of organisms. Therefore, life in a lake or the ocean is generally divided into zones. The zones correlate mainly with the amount of sunlight and nutrients available to producers. **Figure 1** shows ocean zones. Lakes have similar zones.

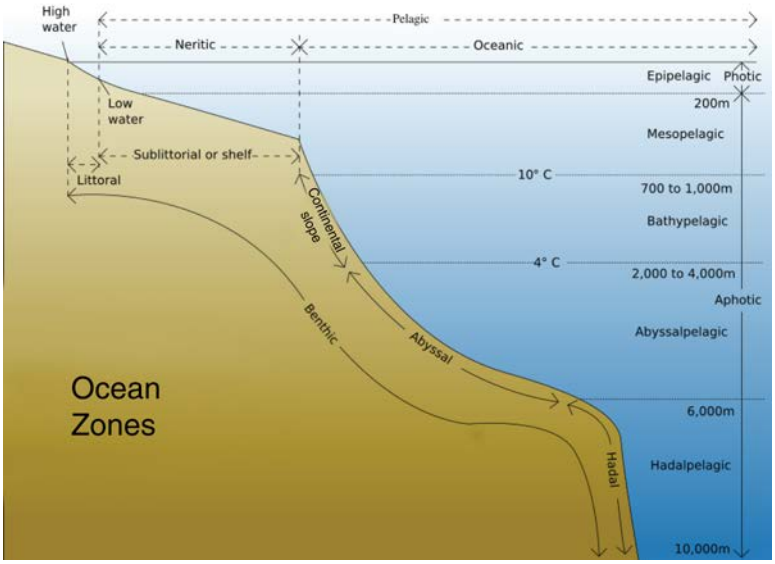

Figure 16.10: The ocean is divided into many different zones, depending on distance from shore and depth of water. The pelagic zone is divided into neritic and oceanic zones based on distance from shore. Into what additional zones is the pelagic zone divided on the basis of water depth? What additional zones make up the benthic zone?

- The **littoral zone** is the shallow water near the shore. In the ocean, the littoral zone is also called the intertidal zone.
- The **pelagic zone** is the main body of open water farther out from shore. It is divided into additional zones based on water depth. In the ocean, the part of the pelagic zone

over the continental shelf is called the **neritic zone,** and the rest of the pelagic zone is called the **oceanic zone.**
- The **benthic zone** is the bottom surface of a body of water. In the ocean, the benthic zone is divided into additional zones based on depth below sea level.

Aquatic Organisms

Aquatic organisms are classified into three basic categories: plankton, nekton, and benthos. Organisms in these three categories vary in where they live and how they move.

- **Plankton** are aquatic organisms that live in the water itself and cannot propel themselves through water. They include both phytoplankton and zooplankton. Phytoplankton are bacteria and algae that use sunlight to make food by photosynthesis. Zooplankton are tiny animals that feed on phytoplankton.
- **Nekton** are aquatic animals that live in the water and can propel themselves by swimming or other means. Nekton include invertebrates such as shrimp and vertebrates such as fish.
- **Benthos** are aquatic organisms that live on the surface below a body of water. They live in or on the sediments at the bottom. Benthos include sponges, clams, and sea stars (see **Figure 2**).

Marine Biomes

Marine biomes are aquatic biomes found in the salt water of the ocean. Major marine biomes are neritic, oceanic, and benthic biomes. Other marine biomes include intertidal zones, estuaries, and coral reefs.

Neritic Biomes

Neritic biomes occur in ocean water over the continental shelf (see **Figure 1**). They extend from the low-tide water line to the edge of the continental shelf. The water here is shallow, so there is enough sunlight for photosynthesis. The water is also rich in nutrients, which are washed into the water from the nearby land. Because of these favorable conditions, large populations of phytoplankton live in neritic biomes. They produce enough food to support many other organisms, including both zooplankton and nekton. As a result, neritic biomes have relatively great biomass and biodiversity. They are occupied by many species of invertebrates and fish. In fact, most of the world's major saltwater fishing areas are in neritic biomes.

Figure 16.11: This sea star, or starfish, is an example of a benthic organism. The tiny white projections on the bottom surface of the sea star allow it anchor to, or slowly crawl over, the bottom surface of the ocean.

Oceanic Biomes

Oceanic biomes occur in the open ocean beyond the continental shelf. There are lower concentrations of dissolved nutrients away from shore, so the oceanic zone has a lower density of organisms than the neritic zone. The oceanic zone is divided into additional zones based on water depth (see **Figure 1**).

- The **epipelagic zone** is the top 200 meters of water, or the depth to which enough sunlight can penetrate for photosynthesis. Most open ocean organisms are concentrated in this zone, including both plankton and nekton.
- The **mesopelagic zone** is between 200 and 1,000 meters below sea level. Some sunlight penetrates to this depth but not enough for photosynthesis. Organisms in this zone consume food drifting down from the epipelagic zone, or they prey upon other organisms in their own zone. Some organisms are detrivores, which consume dead organisms and organic debris that also drift down through the water.
- The **bathypelagic zone** is between 1,000 and 4,000 meters below sea level. No sunlight penetrates below 1,000 meters, so this zone is completely dark. Most organisms in this zone either consume dead organisms drifting down from above or prey upon other animals in their own zone. There are fewer organisms and less biomass here than in higher zones. Some animals are bioluminescent, which means they can give off light (see **Figure 3**). This is an adaptation to the total darkness.

- The **abyssopelagic zone** is between 4,000 and 6,000 meters below sea level. The **hadopelagic zone** is found in the water of deep ocean trenches below 6,000 meters. Both of these zones are similar to the bathypelagic zone in being completely dark. They have even lower biomass and species diversity.

Figure 16.12: The anglerfish lives in the bathypelagic zone. The rod-like structure protruding from the anglerfish's face is tipped with bioluminescent microorganisms. The structure wiggles like a worm to attract prey. Only the "worm" is visible to prey in the total darkness of this zone.

Benthic Biomes

Benthic biomes occur on the bottom of the ocean where benthos live. Some benthos, including sponges, are sessile, or unable to move, and live attached to the ocean floor. Other benthos, including clams, burrow into sediments on the ocean floor. The benthic zone can be divided into additional zones based on how far below sea level the ocean floor is (see **Figure 1**).

- The **sublittoral zone** is the part of the ocean floor that makes up the continental shelf near the shoreline. The water is shallow enough for sunlight to penetrate down to the ocean floor. Therefore, photosynthetic producers such as seaweed can grow on the ocean floor in this zone. The littoral zone is rich in marine life.

- The **bathyal zone** is the part of the ocean floor that makes up the continental slope. It ranges from about 1,000 to 4,000 meters below sea level. The bathyal zone contains no producers because it is too far below the surface for sunlight to penetrate. Although consumers and decomposers live in this zone, there are fewer organisms here than in the sublittoral zone.
- The **abyssal zone** is the part of the ocean floor in the deep open ocean. It varies from about 4,000 to 6,000 meters below sea level. Organisms that live on the ocean floor in this zone must be able to withstand extreme water pressure, continuous cold, and scarcity of nutrients. Many of the organisms sift through sediments on the ocean floor for food or dead organisms.
- The **hadal zone** is the ocean floor below 6,000 meters in deep ocean trenches. The only places where organisms are known to live in this zone are at hydrothermal vents, where invertebrates such as tubeworms and clams are found. They depend on microscopic archaea organisms for food. These tiny chemosynthetic producers obtain energy from chemicals leaving the vents (see the *Principles of Ecology* chapter).

Intertidal Zone

The **intertidal zone** is a narrow strip along the coastline that falls between high- and low-tide water lines. It is also called the littoral zone (see **Figure 1**). A dominant feature of this zone is the regular movement of the tides in and out. In most areas, this occurs twice a day. Due to the tides, this zone alternates between being under water at high tide and being exposed to the air at low tide. An intertidal zone is pictured in **Figure 4**.

The high tide repeatedly brings in coastal water with its rich load of dissolved nutrients. There is also plenty of sunlight for photosynthesis. In addition, the shallow water keeps large predators, such as whales and big fish, out of the intertidal zone. As a result, the intertidal zone has a high density of living things. Seaweeds and algae are numerous, and they support many consumer species, either directly or indirectly, including barnacles, sea stars, and crabs.

Other conditions in the intertidal zone are less favorable. For example, there are frequent shifts from a water to an air environment. There are also repeated changes in temperature and salinity (salt concentration). These changing conditions pose serious challenges to marine organisms. The moving water poses yet another challenge. Organisms must have some way to prevent being washed out to sea with the tides. Barnacles, like those in **Figure 5**, cement themselves to rocks. Seaweeds have rootlike structures, called holdfasts, which anchor them to rocks. Crabs burrow underground to avoid being washed out with the tides.

Figure 16.13: These pictures show the Bay of Fundy off the northeastern coast of Maine in North America. The picture on the left shows the bay at high tide, and the picture on the right shows the bay at low tide. The area covered by water at high tide and exposed to air at low tide is the intertidal zone.

Figure 16.14: Barnacles secrete a cement-like substance that anchors them to rocks.

Other Marine Biomes

The intertidal zone has high biodiversity. However, it is not the marine biome with the highest biodiversity. That distinction goes to estuaries and coral reefs. They have the highest biodiversity of all marine biomes.

- An **estuary** is a bay where a river empties into the ocean. It is usually semi-enclosed, making it a protected environment. The water is rich in dissolved nutrients from the river and shallow enough for sunlight to penetrate for photosynthesis. As a result, estuaries are full of marine life. **Figure 6** shows an estuary on the California coast near San Francisco.

Figure 16.15: This satellite photo shows the San Francisco Estuary on the California coast. This is the largest estuary on the lower west coast of North America. Two rivers, the Sacramento and the San Joaquin, flow into the estuary (upper right corner of photo). The estuary is almost completely enclosed by land but still connected to the ocean.

- A **coral reef** is an underwater limestone structure produced by tiny invertebrate animals called corals. Coral reefs are found only in shallow, tropical ocean water. Corals

secrete calcium carbonate (limestone) to form an external skeleton. Corals live in colonies, and the skeletal material gradually accumulates to form a reef. Coral reefs are rich with marine organisms, including more than 4,000 species of tropical fish. **Figure 7** shows a coral reef in the Hawaiian Islands.

Figure 16.16: Colorful fish swim in warm, shallow ocean water near a coral reef off the Hawaiian Islands.

Freshwater Biomes

Freshwater biomes occur in water that contains little or no salt. Freshwater biomes include standing water and running water biomes.

Standing Freshwater Biomes

Standing freshwater biomes include ponds and lakes. Ponds are generally smaller than lakes and shallow enough for sunlight to reach all the way to the bottom. In lakes, at least some of the water is too deep for sunlight to penetrate. As a result, like the ocean, lakes can be divided into zones based on availability of sunlight for producers.

- The littoral zone is the water closest to shore. The water in the littoral zone is generally shallow enough for sunlight to penetrate, allowing photosynthesis. Producers in this zone include both phytoplankton and plants that float in the water. They provide food, oxygen, and habitat to other aquatic organisms. The littoral zone generally has high productivity and high biodiversity.

- The **limnetic zone** is the top layer of lake water away from shore. This zone covers much of the lake's surface, but it is only as deep as sunlight can penetrate. This is a maximum of 200 meters. If the water is muddy or cloudy, sunlight cannot penetrate as deeply. Photosynthesis occurs in this zone, and the primary producers are phytoplankton, which float suspended in the water. Zooplankton and nekton are also found in this zone. The limnetic zone is generally lower in productivity and biodiversity than the littoral zone.
- The **profundal zone** is the deep water near the bottom of a lake where no sunlight penetrates. Photosynthesis cannot take place, so there are no producers in this zone. Consumers eat food that drifts down from above, or they eat other organisms in the profundal zone. Decomposers break down dead organisms that drift down through the water. This zone has low biodiversity.
- The benthic zone is the bottom of a lake. Near the shore, where water is shallow, the bottom of the lake receives sunlight, and plants can grow in sediments there. Organisms such as crayfish, snails, and insects also live in and around the plants near shore. The plants provide shelter from predatory fish as well as food and oxygen. In deeper water, where the bottom of the lake is completely dark, there are no producers. Most organisms that live here are decomposers.

The surface water of a lake is heated by sunlight and becomes warmer than water near the bottom. Because warm water is less dense that cold water, it remains on the surface. When dead organisms sink to the bottom of a lake, they are broken down by decomposers that release the nutrients from the dead organism. As a result, nutrients accumulate at the lake's bottom. In spring and fall in temperate climates, the surface water of a lake reaches the same temperature as the deeper water. This gives the different water layers the same density, allowing them to intermix. This process, called **turnover,** brings nutrients from the bottom of the lake to the surface, where producers can use them.

Lakes can be categorized on the basis of their overall nutrient levels, as shown in **Table 1**. Oligotrophic lakes have low nutrient levels, so they also have low productivity. With few producers (or other aquatic organisms), the water remains clear and little oxygen is used up to support life. Biodiversity is low.

Table 16.2: **Trophic Classification of Freshwater Lakes**

Type of Lake	Nutrient Level	Productivity	Clarity of Water	Oxygen Level
Oligotrophic	Low	Low	High	High
Mesotrophic	Medium	Medium	Medium	Medium
Eutrophic	High	High	Low	Low
Hypertrophic	Very high	Very high	Very low	Very low

Acid rain is another cause of low productivity in lakes. Acid rain falling into a lake causes the lake water to become too acidic for many species to tolerate. This results in a decline in the number and diversity of lake organisms. This has happened to many lakes throughout the northeastern United States. The water in the lakes is very clear because it is virtually devoid of life.Lakes with high nutrient levels have higher productivity, cloudier water, lower oxygen levels, and higher biomass and biodiversity. Very high nutrient levels in lakes are generally caused by contamination with fertilizer or sewage. The high concentration of nutrients may cause a massive increase in phytoplankton, called a phytoplankton bloom (see **Figure 8**). The bloom blocks sunlight from submerged plants and other producers and negatively impacts most organisms in the lake.

Figure 16.17: The phytoplankton bloom on this lake blocks most sunlight from penetrating below the surface, creating a condition detrimental to many other aquatic organisms.

Running Freshwater Biomes

Running freshwater biomes include streams and rivers. Streams are generally smaller than rivers. Streams may start with surface runoff, snowmelt from a glacier, or water seeping out of the ground from a spring. If the land is not flat, the water runs downhill. The water joins other streams and then rivers as it flows over the land. Eventually, the water empties into a pond, lake, or the ocean.

Some species living in rivers that empty into the ocean may live in freshwater during some stages of their life cycle and in salt water during other stages. For example, salmon are born and develop in freshwater rivers and then move downstream to the ocean, where they live as adults. In contrast, some eels are born and develop in the ocean and then move into freshwater rivers to live as adults.Compared with standing water, running water is better able to dissolve oxygen needed by producers and other aquatic organisms. When a river rushes over a waterfall, like the one in **Figure 9**, most of the water is exposed to the air, allowing it to dissolve a great deal of oxygen. Flowing water also provides a continuous supply of nutrients. Some nutrients come from the decomposition of dead aquatic organisms. Other nutrients come from the decomposition of dead terrestrial organisms, and other organic debris such as leaves, that fall into the water.

Figure 16.18: Flowing water forms a waterfall on the South Yuba River in Nevada County, California. As the water falls through the air, it dissolves oxygen needed by aquatic organisms.

Algae are the main producers in running freshwater biomes. If water flows slowly, algae can float suspended in the water, and huge populations may form, like the phytoplankton bloom in **Figure 8** above. If water flows rapidly, algae must attach themselves to rocks or plants to avoid being washed away and generally cannot form very large populations.

Plants are also important producers in most running water biomes. Some plants, such as mosses, cling to rocks. Other plants, such as duckweed, float in the water. If nutrient levels are high, floating plants may form a thick mat on the surface of the water, like the one shown in **Figure 10** (left photo). Still other plants grow in sediments on the bottoms of streams and rivers. Many of these plants—like the cattails in **Figure 10** (right photo)—have long narrow leaves that offer little resistance to the current. In addition to serving as a food source, plants in running water provide aquatic animals with protection from the current and places to hide from predators.

Figure 16.19: The picture on the left shows a thick mat of duckweed floating on a river. The picture on the right shows cattails growing in sediments at the edge of a stream bed. Notice the cattails' long, slender leaves, which reduce water resistance.

Consumers in running water include both invertebrate and vertebrate animals. The most common invertebrates are insects. Others include snails, clams, and crayfish. Some invertebrates live on the water surface, others float suspended in the water, and still others cling to rocks on the bottom. All rely on the current to bring them food and dissolved oxygen. The invertebrates are important consumers as well as prey to the many vertebrates in running water. Vertebrate species include fish, amphibians, reptiles, birds, and mammals. However, only fish live in the water all the time. Other vertebrates spend part of their time on land.

The movement of running water poses a challenge to aquatic organisms, which have adapted in various ways. Some organisms have hooks or threadlike filaments to anchor themselves to rocks or plants in the water. Other organisms, including fish, have fins and streamlined bodies that allow them to swim against the current.The interface between running freshwater and land is called a **riparian zone.** It includes the vegetation that grows along the edge of a river and the animals that consume or take shelter in the vegetation. Riparian zones are very important natural areas for several reasons:

- They filter pollution from surface runoff before it enters a river.
- They help keep river water clear by trapping sediments.
- They protect river banks from erosion by running water.
- They help regulate the temperature of river water by providing shade.

Wetlands

A **wetland** is an area that is saturated or covered by water for at least one season of the year. Freshwater wetlands are also called swamps, marshes, or bogs. Saltwater wetlands include estuaries, which are described earlier in this lesson. Wetland vegetation must be adapted to water-logged soil, which contains little oxygen. Freshwater wetland plants include duckweed and cattails (see **Figure 10**, above). Some wetlands also have trees. Their roots may be partly above ground to allow gas exchange with the air. Wetlands are extremely important biomes for several reasons.

- They store excess water from floods and runoff.
- They absorb some of the energy of running water and help prevent erosion.
- They remove excess nutrients from runoff before it empties into rivers or lakes.
- They provide a unique habitat that certain communities of plants need to survive.
- They provide a safe, lush habitat for many species of animals.

Lesson Summary

- Aquatic biomes are divided into zones based on factors such as water depth and amount of sunlight available for photosynthesis. Aquatic organisms include plankton, nekton, and benthos.
- Marine biomes include neritic, oceanic, and benthic biomes. Intertidal zones, estuaries, and coral reefs are marine biomes with the highest biodiversity.
- Freshwater biomes may be standing water biomes, such as lakes, or running water biomes, such as rivers. Wetlands are biomes in which the ground is saturated or covered by water for at least part of the year.

Review Questions

1. In a large body of standing water, what is the photic zone?
2. State why the oceanic zone has a lower concentration of nutrients than the neritic zone.
3. Why is moving water a major challenge for organisms in the littoral zone of the ocean?
4. Why does the profundal zone of a lake have no producers?
5. A new species of bioluminescent fish has been discovered in the ocean. Which oceanic zone is most likely the home of this fish? Explain your answer.
6. A developer plans to extend a golf course into a riparian biome. Outline environmental arguments you could make against this plan.
7. Compare and contrast plankton, nekton, and benthos.
8. In the deep ocean far from shore, why might you find more dissolved nutrients at the bottom than at the surface?

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Vocabulary

abyssal zone Part of the ocean floor that is under the deep ocean.

abyssopelagic zone Water between 4,000 and 6,000 meters below sea level in the oceanic zone.

aphotic zone Deep water in a lake or the ocean where too little sunlight penetrates for photosynthesis to occur.

bathyal zone Part of the ocean floor that makes up the continental slope.

bathypelagic zone Water between 1,000 and 4,000 meters below sea level in the oceanic zone.

benthic biome Marine biome that occurs on the bottom of the ocean where benthos live.

benthic zone Bottom surface of the ocean or a lake.

benthos Aquatic organisms that live on the surface below a body of water.

coral reef Underwater limestone structure formed by tiny invertebrate animals called corals.

epipelagic zone Top 200 meters of water in the oceanic zone.

estuary Bay where a river empties into the ocean.

freshwater biome Biome such as a lake or river that has water with little or no salt.

hadal zone Part of the ocean floor that is in deep ocean trenches.

hadopelagic zone Water of deep ocean trenches below 6,000 meters in the oceanic zone.

intertidal zone Narrow strip along the coastline of the ocean that falls between high- and low-tide water lines.

limnetic zone Top layer of deep water in a lake, down to the depth that sunlight penetrates.

littoral zone Shallow water near the shore of a lake or the ocean.

marine biome Aquatic biome found in the salt water of the ocean.

mesopelagic zone Water between 200 and 1,000 meters below sea level in the oceanic zone.

nekton Aquatic animals that live in the water itself and can propel themselves by swimming or other means.

neritic biome Marine biome that occurs in ocean water over the continental shelf.

neritic zone Part of the pelagic zone over the continental shelf.

oceanic biome Marine biome that occurs in ocean water beyond the continental shelf.

oceanic zone Part of the pelagic zone beyond the continental shelf.

pelagic zone Main body of open water away from shore in a lake or the ocean.

photic zone Depth of water in a lake or the ocean to which sunlight can penetrate and photosynthesis can occur.

plankton Aquatic organisms that live in the water itself and cannot propel themselves through water.

profundal zone Deep water in a lake near the bottom where no sunlight penetrates.

riparian zone Interface between running freshwater and land.

sublittoral zone Part of the ocean floor that makes up the continental shelf.

turnover Process in which different layers of lake water intermix and bring nutrients from the bottom to the surface.

upwelling Process in which deep ocean water is forced to the surface by currents, bringing dissolved nutrients from the bottom to the surface.

wetland Area that is saturated or covered by water for at least one season of the year.

Points to Consider

Next we discuss community interactions. Abiotic factors such as water depth affect organisms in aquatic biomes. Organisms in all biomes are also affected by biotic factors, which include their interactions with other species.

- How do you think different species interact?
- What types of relationships do you think different species might have with eachother?
- How could these relationships affect the evolution of the species involved?

16.4 Lesson 16.4: Community Interactions

Lesson Objectives

- State the significance of the community in ecology, and list types of community interactions.
- Define predation, and explain how it affects population growth and evolution.
- Describe competition, and outline how it can lead to extinction or specialization of species.
- Define symbiosis, and identify major types of symbiotic relationships.
- Describe ecological succession, and explain how it relates to the concept of a climax community.

Introduction

Biomes as different as grasslands and estuaries share something extremely important. They have populations of interacting species. Moreover, species interact in the same basic ways in all biomes. For example, all biomes have some species that prey on other species for food. Species interactions are important biotic factors in ecological systems. The focus of study of species interactions is the community.

What Is a Community?

In ecology, a **community** is the biotic component of an ecosystem. It consists of populations of different species that live in the same area and interact with one another. Like abiotic factors, such as climate or water depth, species interactions in communities are important biotic factors in natural selection. The interactions help shape the evolution of the interacting species. Three major types of community interactions are predation, competition, and symbiosis.

Predation

Predation is a relationship in which members of one species (the predator) consume members of other species (the prey). The lions and cape buffalo in **Figure 1** are classic examples of predators and prey. In addition to the lions, there is another predator in this figure. Can you find it? The other predator is the cape buffalo. Like the lion, it consumes prey species, in this case species of grasses. Predator-prey relationships account for most energy transfers in food chains and webs (see the *Principles of Ecology* chapter).

Types of Predators

The lions in **Figure 1** are true predators. In **true predation,** the predator kills its prey. Some true predators, like lions, catch large prey and then dismember and chew the prey before eating it. Other true predators catch small prey and swallow it whole. For example, snakes swallow mice whole.

Some predators are not true predators because they do not kill their prey. Instead, they graze on their prey. In **grazing,** a predator eats part of its prey but rarely kills it. For example, deer graze on plants but do not usually kill them. Animals may also be "grazed" upon. For example, female mosquitoes suck tiny amounts of blood from animals but do not harm them, although they can transmit disease.

Figure 16.20: An adult male lion and a lion cub feed on the carcass of a South African cape buffalo.

Predation and Populations

True predators help control the size of prey populations. This is especially true when a predator preys on just one species. Generally, the predator-prey relationship keeps the population size of both species in balance. This is shown in **Figure 2**. Every change in population size of one species is followed by a corresponding change in the population size of the other species. Generally, predator-prey populations keep fluctuating in this way as long as there is no outside interference.

Some predator species are known as **keystone species,** because they play such an important role in their community. Introduction or removal of a keystone species has a drastic effect on its prey population. This, in turn, affects populations of many other species in the community. For example, some sea star species are keystone species in coral reef communities. The sea stars prey on mussels and sea urchins, which have no other natural predators. If sea stars are removed from a coral reef community, mussel and sea urchin populations would have explosive growth, which in turn would drive out most other species and destroy the reef community.

Sometimes humans deliberately introduce predators into an area to control pests. This is called **biological pest control**. One of the earliest pests controlled in this way was a type of insect, called a scale insect. The scale insect was accidentally introduced into California from Australia in the late 1800s. It had no natural predators in California and was destroying the state's citrus trees. Then, its natural predator in Australia, a type of beetle, was introduced into California in an effort to control the scale insect. Within a few years, the insect was completely controlled by the predator. Unfortunately, biological pest control does not always work this well. Pest populations often rebound after a period of decline.

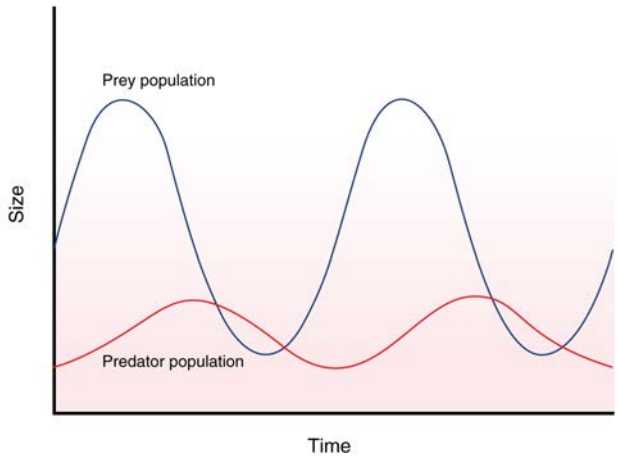

Figure 16.21: As the prey population increases, the predator population starts to rise. With more predators, the prey population starts to decrease, which, in turn, causes the predator population to decline. This pattern keeps repeating. There is always a slight lag between changes in one population and changes in the other population.

Adaptations to Predation

Both predators and prey have adaptations to predation. Predator adaptations help them capture prey. Prey adaptations help them avoid predators. A common adaptation in both predator and prey species is **camouflage,** or disguise. One way of using camouflage is to blend in with the background. Several examples are shown in **Figure 3**.

Figure 16.22: Can you see the crab in the photo on the left? It is camouflaged with algae. The preying mantis in the middle photo looks just like the dead leaves in the background. The stripes on the zebras in the right photo blend the animals together, making it hard to see where one zebra ends and another begins.

Another way of using camouflage is to look like a different, more dangerous animal. Using appearance to "mimic" another animal is called **mimicry. Figure 4** shows an example of mimicry. The moth in the figure has markings on its wings that look like the eyes of an owl. When a predator comes near, the moth suddenly displays the markings. This startles the predator and gives the moth time to fly away.

Figure 16.23: The moth on the left mimics the owl on the right. This "disguise" helps protect the moth from predators.

Some prey species have adaptations that are the opposite of camouflage. They have bright colors or other highly noticeable traits that serve as a warning for their predators to stay away. For example, some of the most colorful butterflies are poisonous to birds, so birds have learned to avoid eating them. By being so colorful, the butterflies are more likely to be noticed—and avoided—by their predators.

Predation, Natural Selection, and Co-evolution

Adaptations to predation come about through natural selection (see the *Evolution in Populations* chapter). When a prey organism avoids a predator, it has higher fitness than members of the same species that were killed by the predator. The organism survives longer and may produce more offspring. As a result, traits that helped the prey organism avoid the predator gradually become more common in the prey population.

Evolution of traits in the prey species leads to evolution of corresponding traits in the predator species. This is called **co-evolution.** In co-evolution, each species is an important factor in the natural selection of the other species. Predator-prey co-evolution is illustrated by rough-skinned newts and common garter snakes, both shown in **Figure 5**. Through natural selection, newts evolved the ability to produce a strong toxin. In response, garter snakes evolved the ability to resist the toxin, so they could still safely prey upon newts. Then, newts evolved the ability to produce higher levels of toxin. This was followed by garter snakes evolving resistance to the higher levels. In short, the predator-prey relationship led to an evolutionary "arms race," resulting in extremely high levels of toxin in newts.

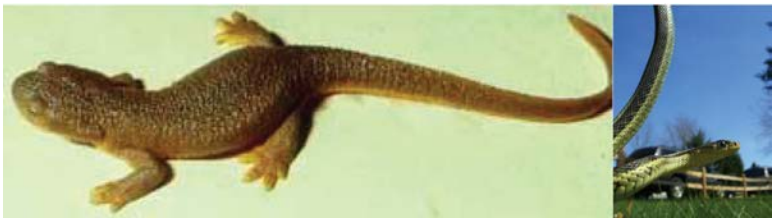

Figure 16.24: The rough-skinned newt on the left is highly toxic to other organisms. Common garter snakes, like the one on the right, have evolved resistance to the toxin.

Competition

Competition is a relationship between organisms that strive for the same limited resources. The resources might be food, nesting sites, or territory. Two different types of competition are intraspecific and interspecific competition.

- **Intraspecific competition** occurs between members of the same species. For example, two male birds of the same species might compete for mates in the same territory. Intraspecific competition is a necessary factor in natural selection. It leads to adaptive changes in a species through time (see the *Evolution in Populations* chapter).
- **Interspecific competition** occurs between members of different species. For example, two predator species might compete for the same prey. Interspecific competition takes place in communities of interacting species. It is the type of competition referred to in the rest of this section.

Interspecific Competition and Extinction

When populations of different species in a community depend on the same resources, there may not be enough resources to go around. If one species has a disadvantage, such as more predators, it may get fewer of the necessary resources. As a result, members of that species are less likely to survive, and the species will have a higher death rate than the other species. Fewer offspring will be produced and the species may eventually die out in the area.

In nature, interspecific competition has often led to the extinction of species. Many other extinctions have occurred when humans introduced new species into areas where they had no predators. For example, rabbits were introduced into Australia in the mid-1800s for sport hunting. Rabbits had no predators in Australia and quickly spread throughout the continent. Many species of Australian mammals could not successfully compete with rabbits and went extinct.

Interspecific Competition and Specialization

Another possible outcome of interspecific competition is the evolution of traits that create distinct differences among the competing species. Through natural selection, competing species can become more specialized. This allows them to live together without competing for the same resources. An example is the anolis lizard. Many species of anolis live and prey on insects in tropical rainforests. Competition among the different species led to the evolution of specializations. Some anolis evolved specializations to prey on insects in leaf litter on the forest floor. Others evolved specializations to prey on insects on the branches of trees. This allowed the different species of anolis to co-exist without competing.

Symbiotic Relationships

Symbiosis is a close association between two species in which at least one species benefits. For the other species, the outcome of the association may be positive, negative, or neutral. There are three basic types of symbiotic relationships: mutualism, commensalism, and parasitism.

Mutualism

Mutualism is a symbiotic relationship in which both species benefit. Lichen is a good example. A lichen is not a single organism but a fungus and an alga. The fungus absorbs water from air and minerals from rock or soil. The alga uses the water and minerals to make food for itself and the fungus. Another example involves goby fish and shrimp (see **Figure 6**). The nearly blind shrimp and the fish spend most of their time together. The shrimp maintains a burrow in the sand in which both the goby and the shrimp live. When a

predator comes near, the fish touches the shrimp with its tail as a warning. Then, both fish and shrimp retreat to the burrow until the predator is gone. Each gains from this mutualistic relationship: the shrimp gets a warning of approaching danger, and the fish gets a safe home and a place to lay its eggs.

Figure 16.25: The multicolored shrimp in the front and the green goby fish behind it have a mutualistic relationship. The shrimp shares its burrow with the fish, and the fish warns the shrimp when predators are near. Both species benefit from the relationship.

Co-evolution often occurs in species involved in mutualistic relationships. Many examples are provided by flowering plants and the species that pollinate them. Plants have evolved flowers with traits that promote pollination by particular species. Pollinator species, in turn, have evolved traits that help them obtain pollen or nectar from certain species of flowers. For example, the plant with tube-shaped flowers shown in **Figure 7** co-evolved with hummingbirds. The birds evolved long, narrow beaks that allowed them to sip nectar from the tubular blooms.

Commensalism

Commensalism is a symbiotic relationship in which one species benefits while the other species is not affected. In commensalism, one animal typically uses another for a purpose other than food. For example, mites attach themselves to larger flying insects to get a "free ride," and hermit crabs use the shells of dead snails for shelter.

Co-evolution explains some commensal relationships. An example is the human species and some of the species of bacteria that live inside humans. Through natural selection, many species of bacteria have evolved the ability to live inside the human body without harming it.

Figure 16.26: This hummingbird's long slender beak and the large tubular flowers of the plant are a good match, which resulted from a long period of co-evolution. Their relationship is an example of mutualism. The hummingbird uses nectar from the flowers for food and pollinates the flowers in the process.

Parasitism

Parasitism is a symbiotic relationship in which one species (the parasite) benefits while the other species (the host) is harmed. Some parasites live on the surface of their host. Others live inside their host, entering through a break in the skin or in food or water. For example, roundworms are parasites of the human intestine. The worms produce huge numbers of eggs, which are passed in the host's feces to the environment. Other humans may be infected by swallowing the eggs in contaminated food or water. This usually happens only in places with poor sanitation.

Some parasites eventually kill their host. However, most parasites do not. Parasitism in which the host is not killed is a successful way of life and very common in nature. About half of all animal species are parasitic in at least one stage of their lifecycle. Many plants and fungi are parasitic during some stages, as well. Not surprisingly, most animals are hosts to one or more parasites.

Species in parastic relationships are likely to undergo co-evolution. Host species evolve defenses against parasites, and parasites evolve ways to evade host defenses. For example, many plants have evolved toxins that poison plant parasites such as fungi and bacteria. The microscopic parasite that causes malaria in humans has evolved a way to evade the human immune system. It hides out in the host's blood cells or liver where the immune system cannot find it.

Ecological Succession

Ecological succession is the process by which a whole community of populations changes through time. It occurs following a disturbance that creates unoccupied areas for colonization. The first colonizer species are called **pioneer species.** They change the environment and pave the way for other species to move into the area. Succession occurs in two different ways, depending on the starting conditions: primary succession and secondary succession.

Primary Succession

Primary succession occurs in an area that has never been colonized before. Generally, the area is nothing but bare rock. This type of environment can come about in a number of ways, including:

- Lava can flow from a volcano and harden into rock.
- A glacier can retreat and leave behind bare rock.
- A landslide can uncover a large area of bare rock.

After the disturbance, pioneer species move in first. They include bacteria and lichens that can live on bare rock. Along with wind and water, these pioneer species help to weather the rock and form soil. Once soil begins to form, other plants can move in. At first, the plants include grasses and other species that can grow in thin, poor soil. As more plants grow and die, organic matter is added to the soil. This improves the soil and helps it hold water. The improved soil allows shrubs and trees to move into the area. An example of primary succession is shown in **Figure 8**.

Secondary Succession

Secondary succession occurs in a formerly inhabited area that was disturbed. The disturbance could be a fire, flood, or human action such as logging or farming. Secondary succession can occur faster than primary succession because the soil is already in place. In secondary succession, the pioneer species are plants that are adapted to exploit disturbances rather than bare rock. They typically include plants such as grasses, birch trees, and fireweed. Organic matter from the pioneer species improves the soil so other trees and plants can move into the area. An example of secondary succession is shown in **Figure 9**.

Climax Communities

Many early ecologists thought that a community always went through a predictable series of stages during succession. They also thought that the end result of succession was a final

Figure 16.27: On an island near New Zealand, bare rocks from a volcanic eruption are slowly being colonized by pioneer species.

Figure 16.28: This formerly cultivated farm field in Poland is reverting to deciduous forest in the process of secondary succession.

stage called a **climax community.** The type of climax community was believed to be determined mainly by climate. For example, in mild, wet temperate climates, evergreen rainforests were thought to be the predictable end result of succession. Climax communities were also thought to be very biodiverse. This characteristic, in turn, was believed to make them stable, or resistant to change.

Today, most ecologists think that change, rather than stability, is more characteristic of ecological systems. They argue that most communities are disturbed too often to reach a climax community stage. They also argue that high biodiversity does not always make a community stable. Some communities that have low biodiversity, such as salt marshes, are very resistant to change. On the other hand, some communities that have high biodiversity, such as coral reefs, are easily affected by disturbances. High biodiversity may increase species interactions. This, in turn, may make species more interdependent and communities more likely to change when they are disturbed.

Lesson Summary

- A community is the biotic component of an ecosystem. It consists of populations of interacting species. Types of community interactions are predation, competition, and symbiosis.
- Predation is a relationship in which members of one species consume members of other species. Predation influences population sizes and co-evolution of predator and prey species.
- Competition is a relationship between organisms that strive for the same limited resources. Interspecific competition often leads to extinction of one species. However, it may lead to greater specialization of the species, allowing them to co-exist without competing.
- Symbiosis is a close association between species in which at least one species benefits. Types of symbiotic relationships include mutualism, commensalism, and parasitism.
- Ecological succession is the process by which a whole community changes through time. It occurs following a disturbance. A stable climax community may or may not be the predictable end result of succession.

Review Questions

1. In ecology, what is a community?
2. Define predation and give an example of a predator and its prey.
3. What are two possible outcomes of interspecific competition?
4. List three basic types of symbiotic relationships.
5. What is ecological succession and when does it occur?
6. Assume that a destructive beetle was accidentally introduced to California from Europe. The beetle has no natural predators in California and is becoming a major pest.

Describe how biological pest control might be used to control this beetle.

7. A forest was recently disturbed, and several pioneer species have moved in. Which type of ecological succession is taking place? How do you know?
8. Why do species interactions often lead to co-evolution of the species involved? Give an example to illustrate your answer.
9. Summarize how ideas about ecological succession and climax communities have changed.

Further Reading / Supplemental Links

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Vocabulary

biological pest control Deliberate introduction of a predator species into an area in order to control a pest species.

camouflage Common adaptation in predator and prey species that involves disguise.

climax community Final stage of ecological succession.

co-evolution Evolution of interacting species in which each species is an important factor in the natural selection of the other species.

commensalism Symbiotic relationship in which one species benefits while the other species is not affected.

community Biotic component of an ecosystem.

competition Relationship between organisms that strive for the same limited resources.

ecological succession Process by which a whole community changes through time following a disturbance.

grazing Type of predation in which the predator eats part of its prey but rarely kills it.

intraspecific competition Competition between members of the same species.

interspecific competition Competition between members of different species.

keystone species Predator species that plays an important role in the community by controlling the prey population and, indirectly, the populations of many other species in the community.

mimicry Using appearance to "mimic" another animal.

mutualism Symbiotic relationship in which both species benefit.

parasitism Symbiotic relationship in which one species (the parasite) benefits while the other species (the host) is harmed.

pioneer species First colonizer species in an area undergoing ecological succession.

predation Relationship in which members of one species (the predator) consume members of other species (the prey).

primary succession Ecological succession that occurs in an area that has never been colonized before.

secondary succession Ecological succession that occurs in a formerly inhabited area that was disturbed.

symbiosis Close association between two species in which at least one species benefits.

true predation Type of predation in which the predator kills its prey.

Points to Consider

The size and growth of populations in a community is influenced by species interactions. For example, predator-prey relationships control the population growth of both predator and prey species.

- How would populations grow without these influences?
- What other factors do you think might affect population growth?
- What factors do you think may have affected the growth of the human population?

Image Sources

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Chapter 17

Populations

17.1 Lesson 17.1: Characteristics of Populations

Lesson Objectives

- Recognize that human concern about overpopulation dates to ancient Greek times.
- Explain that Cornucopians believe that technology will solve population problems.
- Connect the study of the biology of natural populations to better understand human population issues.
- Define a biological population.
- Give reasons why biologists study populations.
- Compare the importance of population size to that of population density.
- Explain how conservation biologists use Minimum Viable Population (MVP) and Population Viability Analysis (PVA).
- Explain how patchy habitats influence the distribution of individuals within a population.
- Define and explain the reasons for three patterns of dispersion within populations.
- Describe how population pyramids show the age and sex structures of populations.
- Interpret population pyramids to indicate populations' birth and death rates and life expectancy.
- Analyze the effect of age at maturity on population size.
- Explain the structure and meaning of a generalized survivorship curve.
- Compare and contrast the three basic types of survivorship curves.

Introduction

"Solving the population problem is not going to solve the problems of racism... of sexism... of religious intolerance... of war... of gross economic inequality—But

if you don't solve the population problem, you're not going to solve any of those problems. Whatever problem you're interested in, you're not going to solve it unless you also solve the population problem. Whatever your cause, it's a lost cause without population control." **–Paul Ehrlich, 1996**

(From *Paul Ehrlich and the Population Bomb*, PBS video produced by Canadian biologist Dr. David Suzuki, April 26, 1996.)

What exactly is the **population problem**? How can it be solved?

Humans have shown concern for **overpopulation** since the Ancient Greeks built outposts for their expanding citizenship and delayed age of marriage for men to 30. In 1798, Thomas Malthus predicted that the human population would outgrow its food supply by the middle of the 19th century. That time arrived without a Malthusian crisis, but Charles Darwin nevertheless embraced Malthus' ideas and made them the foundation of his own theory of evolution by natural selection. In a 1968 essay, *The Tragedy of the Commons*, Garrett Hardin exhorted humans to "relinquish their freedom to breed," arguing in the journal, *Science*, that "the population problem has no technical solution," but "requires a fundamental extension in morality." In 1979, the government of China instituted a "birth planning" policy, charging fines or "economic compensation fees" for families with more than one child. Others have opposing views, however. Julian Simon, professor of Business Administration and Senior Fellow at the Cato Institute, argued that *The Ultimate Resource* is population, because people and markets find solutions to any problems presented by overpopulation. A group known as **cornucopians** continues to promote the view that more is better.

Would you support a law forbidding you to marry until a certain age? Do you know how such a law would affect population growth? Would you limit the size of all families to one child (**Figure** 17.1)? Do you believe families should welcome as many children as possible? Should these decisions be regulated by law, or by individual choice? Clearly, the "population problem" reaches beyond biology to economics, law, morality, and religion. Although the latter subjects are beyond the scope of this text, the study of population biology can shed some light on human population issues. Let's look at what biologists have learned about natural populations. Later, we will look more closely at human populations, and compare them to populations in nature.

Measuring Populations

In biology, a **population** is a group of organisms of a single species living within a certain area. Ecologists study populations because they directly share a common gene pool. Unlike the species as a whole, members of a population form an interbreeding unit. Natural selection acts on individuals within populations, so the gene pool reflects the interaction between a population and its environment.

Biologists study populations to determine their health or stability, asking questions such as:

Figure 17.1: The Chinese government mandates population control by charging "economic compensation fees" for families with more than one child.

- Is a certain population of endangered grizzly bears growing, stable, or declining?
- Is an introduced species such as the zebra mussel or purple loosestrife growing in numbers?
- Are native populations declining because of an introduced species?
- What factors affect the growth, stability, or decline of a threatened population?

The first step in characterizing the health of a population is measuring its size. If you are studying the population of purple loosestrife plants on your block , you can probably count each individual to obtain an accurate measure of the population's size. However, measuring the population of loosestrife plants in your county would require sampling techniques, such as counting the plants in several randomly chosen small plots and then multiplying the average by the total area of your county. For secretive, highly mobile, or rare species, traps, motion-detecting cameras, or signs such as nests, burrows, tracks, or droppings allow estimates of population size.

Figure 17.2: Purple loosestrife plant populations show patchiness due to uneven distribution of their wetland habitats, and clumped dispersion, due to local variation in soils.

Two problems with absolute size lead ecologists to describe populations in other terms. First, because your county may not be the same size as others, the total number of individuals is less meaningful than the **population density** of individuals – the number of individuals per unit area or volume. Ecologists use population densities more often for comparisons over space or time, although total number is still important for threatened or endangered species.

Concern about threatened and endangered species has led conservationists to attempt to define **minimal viable population** size for some species. A species' **MVP** is the smallest number of individuals which can exist without extinction due to random catastrophic variations in environmental (temperature, rainfall), reproduction (birth rates or age-sex structure), or genetic diversity. In 1978, Mark Shaffer incorporated an estimate for grizzly bear MPV into the first **Population Viability Analysis (PVA)**, a model of interaction between a species and the resources on which it depends. PVAs are species-specific, and require

a great deal of field data for accurate computer modeling of population dynamics. PVAs can predict the probability of extinction, focus conservation efforts, and guide plans for sustainable management.

Patterns in Populations I: in Space (or Patterns in Space)

A second problem in measuring population size relates to the distribution of individuals within the population's boundaries. If your county has extensive wetlands in the southern half, but very few in the north, a countywide population density estimate of purple loosestrife, which grows primarily in shallow freshwater pond edges, marshes, and fens, would be misleading (**Figure** 17.2). **Patchy** habitat – scattered suitable areas within population boundaries – inevitably leads to a patchy distribution of individuals within a population. On a smaller scale, plants within even a single wetland area may be **clumped or clustered** (grouped), due to soil conditions or gathering for reproduction. The characteristic pattern of spacing of individuals within a population is **dispersion** (**Figure** 17.3). Clumped dispersion is most common, but species that compete intensely, such as cactus for water in a desert, show **uniform**, or evenly spaced, dispersion.

Figure 17.3: Populations of cacti in the desert, such as this group of cholla, show uniform, or even, dispersion due to fierce competition for water. The diagrams to the right show nearly uniform (top), random (middle), and clumped (bottom) dispersion patterns.

Other species, whose individuals do not interact strongly, show a **random**, or unpredictable, distribution. Useful measures of population density must take into account both patchiness of habitat and dispersion of individual organisms within the population's boundaries.

Figure 17.4: Grizzly bear populations include adults up to 25 or 30 years old, capable of reproducing, and young immature bears under 6 years old. Healthy populations include roughly equal proportions of each age group.

Age-Sex Structure of a Population

Density and dispersion describe a population's size, but size is not everything. Consider three populations of endangered grizzly bears, each containing one individual per 20 km^2, and a total of 100 individuals in 2,000 km^2. These populations are "equal" with respect to size. One population, however, has 50 immature (non-reproducing young) bears and 50 adult bears able to reproduce. A second population has the same number of immature and adult bears, but of the 50 adults, 45 are male. The third population has 30 immature bears and 70 bears of reproductive age. Which population is healthiest (**Figure** 17.4)?

The answer is not simple, but age and sex differences between populations are significant indicators of health. Biologists concerned about a population's future study age and sex within the population and then graph the results to show the **age-sex structure** as a **population pyramid,** although the result does not always resemble a pyramid. The X-axis in this double bar graph indicates percentage of the population, with males to the left and females to the right. The Y-axis indicates age groups from birth to old age.

The population in the generalized example (**Figure** 17.5) contains a large proportion of young individuals, suggesting a relatively high **birth rate** (number of births per individual within the population per unit time). The bars narrow at each age interval, showing that a significant number of individuals die at every age. This relatively high **death rate** (number of deaths per individual within the population per unit time) indicates a short **life expectancy**, or average survival time for an individual. Note the slightly greater proportion of females compared to males at each age level. Careful study could determine whether the cause for this imbalance is the ratio of female to male births, or higher death rates for

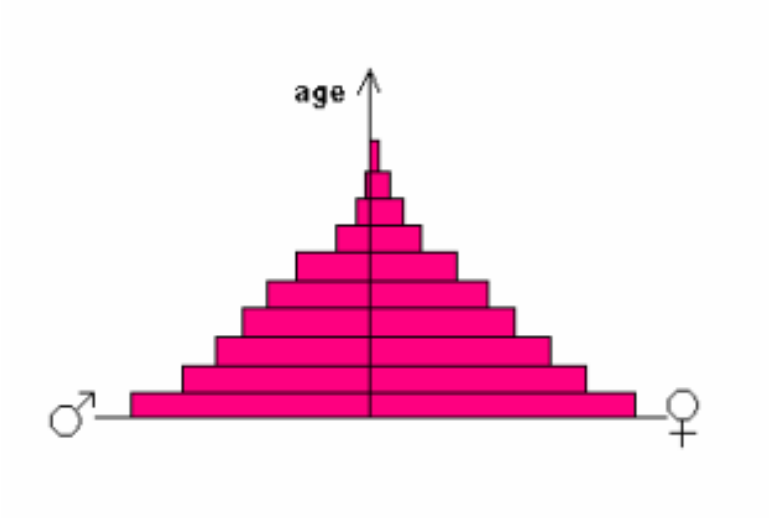

Figure 17.5: A generalized age-sex structure or population pyramid shows the proportion of males and females (X-axis) at each age level (Y-axis). This example shows a slightly higher proportion of females compared to males, and a much higher proportion of young individuals compared to old.

males throughout a shorter lifespan. You will learn in a later lesson that this pattern is characteristic of human populations in less developed countries.

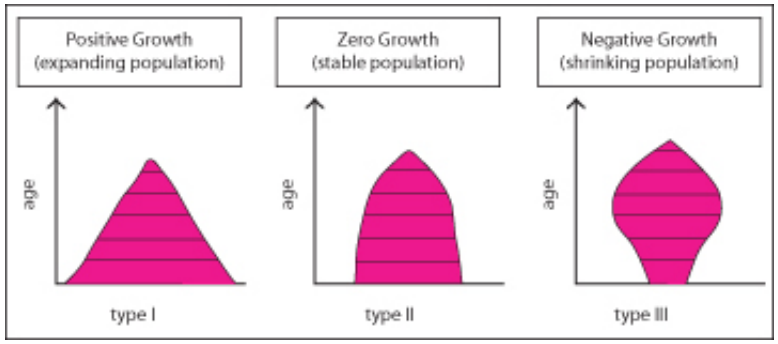

Figure 17.6: Age structures can reveal a population's health. Type I, with most individuals below reproductive age, often indicates a growing population. Type II, with roughly equal proportions of the population at each age level, indicates a stable population. Type III, with more individuals at (or above!) reproductive age than young, describes a declining population.

A population's age structure may reveal its health (**Figure** 17.6). A growing population (Type I) usually has more young individuals than adults at beyond reproductive age. A stable population (Type II) often has roughly equal numbers of young members and adults. A declining population shows more adults and fewer young (Type III). Sex structure may

also affect the health of a population. Sex determination in sea turtles, for example, is temperature-dependent; lower egg incubation temperatures produce males, while temperatures as little as 1-2°C higher produce females (**Figure** 17.7). Some biologists predict that climate change may result in sea turtle sex structure shifts toward females, which could further endanger already threatened species. Continued monitoring of age-sex structures among sea turtles might be able to detect such changes before they become irreversible.

Figure 17.7: The sex of a sea turtle is determined by the temperature at which it develops – males in cooler temperatures, and females in temperatures as little as 1-2C warmer. Climate change may threaten natural sex ratios. Such changes would be reflected in changing age-sex structure pyramids.

Although it is not shown in population pyramids, an important factor affecting population size is the age at which individuals become able to reproduce (**Table** 17.1). Recall that **age at maturity** (when reproduction becomes possible) was the factor that even ancient Greeks recognized could affect population growth, when they prohibited marriage for males under the age of 30. We will return to this relationship in a later lesson, but for now, try to grasp it intuitively: if a person delays reproduction until age 30 and then has one child each year for two years, his or her **fertility** is 2. A person who has two children, one each year, beginning at age 20 also has a fertility of 2. Assume that these four children are born in the same two-year period, and that each offspring reproduces two children at the same age as his/her parent did. Sixty years after the initial four childbirths, the "delayed reproduction" individual will have 2 X 2 X 2 = 8 descendants. However, the early reproducing family will have 2 X 2 X 2 X 2 = 16 offspring – double the population increase of the first family. Do you think this could this be one way to slow human population growth?

Table 17.1: **Number of Offspring Produced Over Time**

Age at First Reproduction	Initial Reproduction	20 years later	30 years later	40 years later	60 years later
20 years	Generation 1: 2 offspring	Generation 2: 4 offspring		Generation 3: 8 offspring	Generation 4: **16**
30 years	Generation 1: 2 offspring		Generation 2: 4 offspring		Generation 3: **8**

Patterns in Populations Through Time

The characteristics of populations introduced above – birth rate, death rate, and life expectancy – interact to form several basic strategies for survival. Insurance companies began investigations into life expectancies for various groups of people – males vs. females, for example – and compiled the data in *life tables.* Biologists plot these patterns through time in **survivorship curves**, which graph the number of all individuals still living (in powers of ten, on the Y-axis) for each age (on the X-axis). The three basic types of survivorship curves are illustrated in **Figure** 17.8.

Species showing a Type I pattern have the highest survival rates, with most individuals living to old age. Many large animals, including humans, show this "late loss" pattern of survivorship; few offspring, high levels of parental care, and low "infant" death rates characterize Type I species. As we will see in a later lesson, human populations in rich countries fit this pattern more closely than do those in undeveloped countries.

Species with Type III survivorship patterns experience high death rates among offspring; relatively few survive to old age. Most plants and invertebrates and many fish show this "early loss" pattern. Parents invest most of the reproductive energy in high numbers of offspring to offset the high death rates, and little or no energy remains for parental care.

Species showing intermediate, Type II survivorship curves experience uniform death rates throughout their lives. Some birds and many asexual species show this "constant loss" pattern.

We'll look at these strategies more closely in the next lesson as we study how populations grow and change: population dynamics.

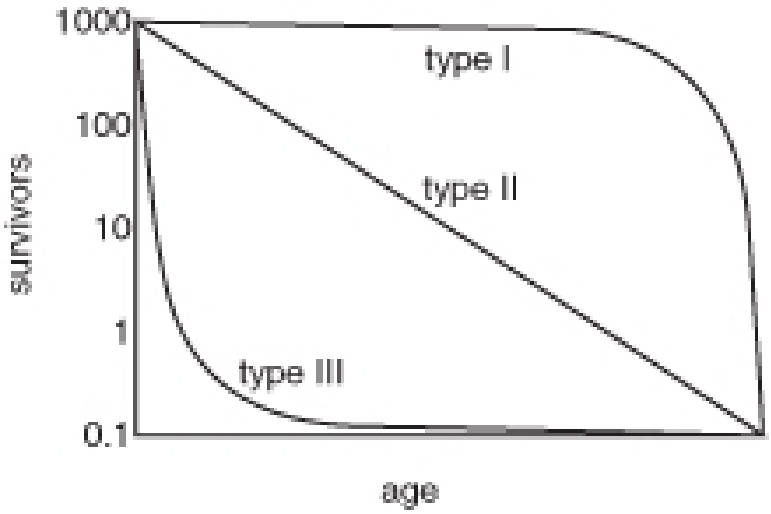

Figure 17.8: Survivorship curves correlate with strategies species use to adapt to various environments. Large organisms in relatively stable environments have few offspring but high levels of parental care; most individuals survive to old age (Type I). Smaller organisms in less stable environments produce many offspring but provide little parental care, and few survive to old age (Type III). Type II species show intermediate characteristics in response to a death rate which remains constant throughout life.

Lesson Summary

- Historic concern with overpopulation includes ancient Greek delay of marriage, Malthus' predictions of a resource crisis, and Darwin's use of exponential growth in his theory of natural selection.
- A group lead by Julian Simon, cornucopians, believes that more people are better, because technology and innovation will solve population problems.
- The study of the biology of natural populations can shed light on human population issues.

- In biology, a population is a group of organisms of a single species living within a certain area.
- Population size, the total number of individuals, is important for understanding endangered or threatened species, but population density is often more useful for comparing populations across time or space.
- Minimum Viable Population (MVP) and Population Viability Analysis (PVA) use extensive field data to predict best management practices for a particular species in conservation biology.

- Double bar graph population pyramids show proportions of males and females within age groups.

- Population pyramids which have wide bases indicate high birth rates and probable population growth, and decreases from one age group to the next indicate death rates and (overall) life expectancy. Populations with narrow bases indicate low birth rates and shrinking populations, and those with bases roughly equal to peaks indicate stable populations and/or low death rates.
- Delaying reproduction or increasing age to sexual maturity can decrease population growth rate, even if fertility levels remain the same.

- Patchy habitat distribution results in patchy distribution of a population throughout its boundaries.
- Dispersion of a population within its boundaries depends on intraspecies competition or cooperation.

1. Clumped distribution indicates social relationships or recent reproduction without dispersal.
2. Uniform distribution reveals competition among individuals for a limited resource.
3. Random distribution suggests little interaction among individuals.

- Survivorship curves show the number of individuals which survive (on a power-of-ten scale) at each age level.

1. Large animals, which provide few offspring with high levels of parental care, experience low death rates and long average life expectancy – a Type I pattern. This pattern is typical for humans in rich/developed countries.
2. Among plants and many invertebrates which have many offspring but little or no parental care, offspring have high death rates and relatively low average life expectancy – a Type III pattern.
3. Some birds and many asexually reproducing species have constant death rates throughout life and intermediate average life expectancy – a Type II pattern.

Review Questions

1. Compare the cornucopian perspective on human population growth to the Malthus' (sometimes called the Neo-Malthusian) view.
2. (If false, restate to make true.) Human concern about overpopulation is a recent phenomenon.
3. Define a biological population.
4. Define and compare the importance of population size vs. population density.
5. Explain how conservation biologists use Minimum Viable Population (MVP) and Population Viability Analysis (PVA).
6. How does patchy distribution differ from dispersion?

7. What types of information do population pyramids show? What kinds of inferences can you make using variations in population pyramid shape?
8. How does delaying reproduction affect population size, even if fertility remains constant?
9. Describe the three types of survivorship curves and the reproductive strategies they illustrate.
10. Apply what you have learned so far about population biology to your current understanding of human populations. Note: we will explore human populations in detail in a future lesson, so accept that your current understanding may be incomplete!

Further Reading / Supplemental Links

- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookpopecol.html
- http://www.geography.learnontheinternet.co.uk/topics/popn1.html
- http://www.census.gov/ipc/www/idb/faq.html
- http://www.biologicaldiversity.org/swcbd/species/orca/pva.pdf
- http://nationalzoo.si.edu/ConservationAndScience/EndangeredSpecies/PopViability/default.cfm

Vocabulary

age at maturity The age at which individuals (sometimes considered only for females) become able to reproduce.

age-sex structure A graphical depiction of proportions of males and females across all age groups within a population; also depicted as a population pyramid.

birth rate (b) The number of births within a population or subgroup per unit time; in human demography, the number of childbirths per 1000 people per year.

cornucopian A person who believes that people and markets will find solutions to any problems presented by overpopulation.

death rate (d) The number of deaths within a population or subgroup per unit time; in human demography, the number of deaths per 1000 people per year.

dispersion The pattern of spacing among individuals within a population – clumped (clustered or grouped), uniform (evenly spaced), or random (no discernible pattern).

life expectancy Average survival time for individuals within a population.

minimum viable population The smallest number of individuals which can exist without extinction due to chance variations in reproduction, genetics, or environment.

overpopulation A condition in which the number of individuals in a population exceeds the carrying capacity of their environment.

population A group of organisms of a single species living within a certain area.

population density The number of organisms per unit area or volume.

population viability analysis A model of interaction between a species and the resources on which it depends used in conservation biology.

survivorship curve Graph which shows the number of all individuals still living (in powers of 10, on the Y-axis) at each age (on the X-axis).

Points to Consider

- Do you think Earth's human population has a patchy distribution? Why or why not?
- Do people show clumped, uniform, or random dispersion? Why?
- How do you think birth rates compare with death rates in the human population? Predict the shape of a population pyramid for humans.
- At this point in your study of population biology, do you consider yourself a Malthusian, following the ideas of Thomas Malthus, or a cornucopian?

17.2 Lesson 17.2: Population Dynamics

Lesson Objectives

- Define population dynamics.
- Describe exponential (J-curve) growth, and explain the conditions under which it occurs.
- Explain Malthus' ideas about human population growth and their significance to evolutionary theory.
- Births and deaths: Balancing costs of reproduction and survival.
- Clarify the relationship between population growth rate, birth rate, and death rate.
- Compare trade-offs between survival and reproduction for *altricial* species to those of *precocial* and *nest parasite* species.
- Describe the relationship between age at maturity and growth rate.

- Analyze the equation for population growth rate.
- Describe several means of dispersal, and its importance to population density.
- Define migration and explain possible effects on population density and growth.
- Compare nomadism, irruption, range expansion, and colonization in terms of their effects on population density.
- Give examples of population growth patterns in nature.
- Describe logistic (S-curve) growth, and explain the conditions under which it occurs.
- Analyze the concept of carrying capacity in terms of population growth and resource availability.
- Compare and contrast density-dependent and density-independent limiting factors.
- Relate predator-prey cycles to density-dependent population control.
- Compare and contrast the adaptations and environmental characteristic of r-selected species to those of K-selected species.

Introduction

Imagine a huge bowl of your favorite potato salad, ready for a picnic on a beautiful, hot, midsummer day. The cook was careful to prepare it under strictly sanitary conditions, using fresh eggs, clean organic vegetables, and new jars of mayonnaise and mustard. Familiar with food poisoning warnings, s/he was so thorough that only a single bacterium made it into that vast amount of food. While such a scenario is highly unrealistic without authentic canning, it will serve as an example as we begin our investigation of how populations change, or **population dynamics**. Because potato salad provides an ideal environment for bacterial growth, just as your mother may have warned, we can use this single bacterial cell in the potato salad to ask:

How Do Populations Grow Under Ideal Conditions?

Given food, warm temperatures, moisture, and oxygen, a single aerobic bacterial cell can grow and divide by binary fission to become two cells in about 20 minutes. The two new cells, still under those ideal conditions, can each repeat this performance, so that after 20 more minutes, four cells constitute the population. Given this modest doubling, how many bacteria do you predict will be happily feeding on potato salad after five hours at the picnic? After you've thought about this, compare your prediction with the "data" in **Table ??**.

Table 17.2: Like many populations under ideal conditions, bacteria show exponential or geometric growth. Each bacterium can undergo binary fission every 20 minutes. After 5 hours, a single bacterium can produce a population of 32,768 descendants.

Table 17.2:

Time (Hours and Minutes)	**Population Size** (Number of Bacteria)
0	1
20 minutes	2
40 minutes	4
1 hour	8
1 hour 20 minutes	16
1 hour 40 minutes	32
2 hours	64
2 hours 20 minutes	128
2 hours 40 minutes	256
3 hours	512
3 hours 20 minutes	1024
3 hours 40 minutes	2048
4 hours	4096
4 hours 20 minutes	8192
4 hours 40 minutes	16,384
5 hours	**32,768**

(*Source:* CK-12 Foundation, *License:* CC-BY-SA)

Are you surprised? This phenomenal capacity for growth of living populations was first described by Thomas Robert Malthus in his 1798 *Essay on the Principle of Population.* Although Malthus focused on human populations, biologists have found that many populations are capable of this explosive reproduction, if provided with ideal conditions. This pattern of growth is **exponential**, or **geometric growth**: as the population grows larger, the rate of growth increases. If you have worked compound interest problems in math or played with numbers for estimating the interest in your savings account, you can compare the growth of a population under ideal conditions to the growth of a savings account under a constant rate of compound interest. The graph in **Figure** 17.9, using potato salad bacterial "data," shows the pattern of exponential growth: the population grows very slowly at first, but more and more rapidly as time passes.

Of course, if bacterial populations always grew exponentially, they would long ago have covered the Earth many times over. While Thomas Malthus emphasized the importance of exponential growth on population, he also stated that ideal conditions do not often exist in nature. A basic limit for all life is energy. Growth, survival, and reproduction require energy. Because energy supplies are limited, organisms must "spend" them wisely. We will end this lesson with a much more realistic model of population growth and the implications of its limits, but first, let's look more carefully at the characteristics of populations which allow them to grow.

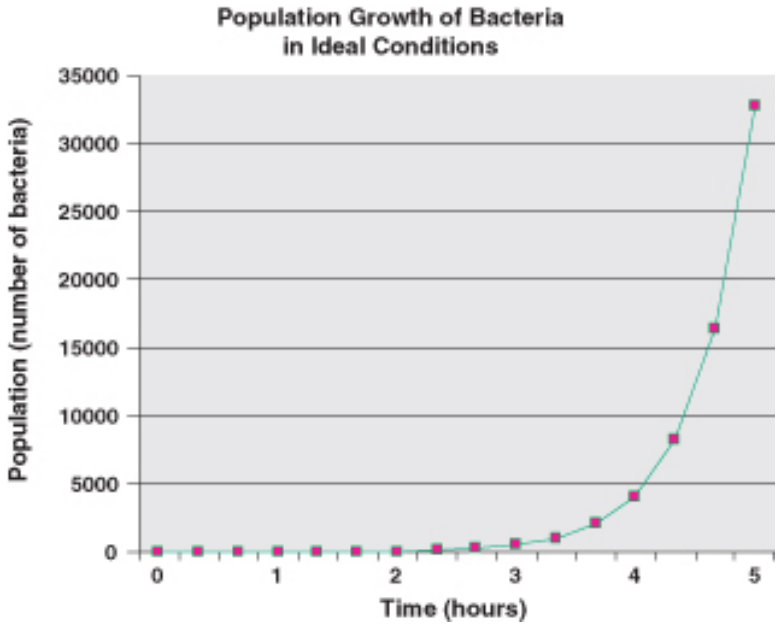

Figure 17.9: Exponential or geometric growth is very slow at first, but accelerates as the population grows. Because rate of growth depends on population size, growth rate increases as population increases. Most populations have the ability to grow exponentially, but such growth usually occurs only under ideal conditions that are not found in nature. Note the "J" shape of the curve.

Births and Deaths: Balancing Costs of Reproduction and Survival

The **growth rate of a population** is the change in population size per member of the population per unit of time. The symbol r denotes growth rate. Growth rate clearly depends on **birth rate** b, the number of births per individual within the population per unit of time, as well a **death rate** d, the number of deaths per individual per unit of time. The following equation calculates growth rate, according to our preliminary understanding:

$$\boldsymbol{r = b - d}$$

growth rate = birth rate – death rate

If birth rate exceeds death rate, r is positive and the population grows. If death rate exceeds birth rate, r is negative and the population declines. And if birth rate and death rate are in equilibrium, growth rate is zero, and the population remains stable. In a stable population, each individual, on the average, produces one offspring which survives long enough to reproduce itself. Mere survival is not success in the game of life; natural selection requires that survivors reproduce. As Malthus realized, nearly all species have the *potential* to grow – to reproduce many more than just a single replacement offspring. However, species vary in the strategies they use to achieve reproductive success, making trade-offs between the energy and time "costs" of survival and those of reproduction. Age at first reproduction, frequency of reproduction, number of offspring, parental care, reproductive lifespan, and offspring death rate are some of the traits which build strategies for successful reproduction.

Analyzing extreme examples can help you understand the trade-offs species must make between survival and reproductive success. Let's compare two groups of birds. Somewhat like precocious children who mature early, *precocial* birds run around to find their own food soon after hatching. Geese, ducks, and chickens use this strategy for raising their young (**Figure** 17.10). Often living and nesting on the ground, precocial species are subject to high predation rates, so few survive long enough to reproduce. Therefore, those who do reproduce lay many eggs at once, and these eggs are large. The young emerge well-developed, ready to feed and escape predators soon after hatching. Precocial species invest a great deal of energy in a large number of offspring but do not spend much energy on parental care, because even though some offspring are likely to die, others will survive long enough to reproduce.

Contrast this precocial strategy with the opposite, *altricial* strategy used by robins and hummingbirds (**Figure** 17.11). These birds hatch helpless and naked, completely unprepared for independent life. Parents invest little energy in just a few, small eggs; hummingbirds' eggs are the smallest in the bird world, and average two per nest. However, survival of these offspring matters a great deal, because there are so few. So, parents build elaborate nests safely hidden in trees and invest a great deal of energy hunting for food around-the-clock until the young have developed enough to fledge and find food on their own.

Precocial and altricial birds play by the rules of costs and benefits, each group using a

Figure 17.10: Geese and ducks use a strategy to ensure reproductive success. They invest a great deal of energy in a large number of large eggs, so that young are born well-developed and ready to fend for themselves almost immediately after hatching. Predation on goslings and ducklings is high, but this death rate is offset by a high birthrate. Overall, the population remains stable.

Figure 17.11: Hummingbirds illustrate an reproductive strategy. Very little energy is spent to produce two tiny eggs, but they are enclosed in a secluded nest, usually hidden in a tree. Survival of the offspring is critical because there are only two, so parents invest tremendous amounts of energy finding food for themselves and their young for nearly three weeks. This energy investment allows the offspring to develop to nearly adult size before they fledge into the world of predators and competition.

different strategy. Cowbirds, however, make up their own rules, earning them the title of "parasites" in the bird world. How can a bird be a parasite? Cowbirds are altricial, but they parasitize by laying their eggs in other birds' nests, thereby escaping the high costs of parental care (**Figure** 17.12). Cowbird eggs are usually slightly larger and hatch a little sooner than the host eggs affording cowbird parents a bit of extra energy. "Early bird" hatchlings do indeed "get the worm," easily out-competing their smaller host siblings for parental food deliveries. Sometimes, they are strong enough to ungratefully oust their "sibs" from the nest. On the other hand, host parents occasionally recognize and eject the foreign egg before it hatches. Yellow warblers simply block off the offending egg (along with their own eggs) by building a new nest bottom. They then lay a new clutch of their own eggs (The eggs are not their primary energy investment). A five-"story" nest holds the record for yellow warbler (and cowbird?) determination!

Figure 17.12: A brown-headed cowbird egg in a phoebe's nest illustrates yet another strategy for reproductive success: invest all of your energy in a single egg, just large enough to out-compete your altricial host's eggs, and let the host parents feed your offspring! The right photo shows a male individual of this parasitic species.

Many species fall in between the extremes of precocial and altricial strategies, but all must make trade-offs between the costs of reproduction and those of surviving predation, competition, and disease, in order to ensure that at least one offspring per adult survives long enough to reproduce. It's worth reprising the survivorship curves introduced in the previous lesson to illustrate these trade-offs (**Figure** 17.13). Which curve illustrates the precocial strategy used by ducks, chickens, and grouse? Which curve demonstrates the altricial strategy of robins and hummingbirds? What shape do you think a cowbird's survivorship curve might take?

One more strategy, introduced in the last lesson, involves variation of age at maturity. All other factors being equal (number and size of offspring, survival rates, and more), delayed reproduction lowers population growth rate. Bald eagles require five years of growth before they are able to reproduce. If they were to lay the same number of eggs during their first year, those first-year offspring and several generations of *their* offspring, as well as the parents, would be able to reproduce during that time, tremendously increasing the overall population. By delaying reproduction, bald eagles not only ensure good energy supplies for reproduction at maturity, but also limit population density to suit their large bodied, long-lived life history.

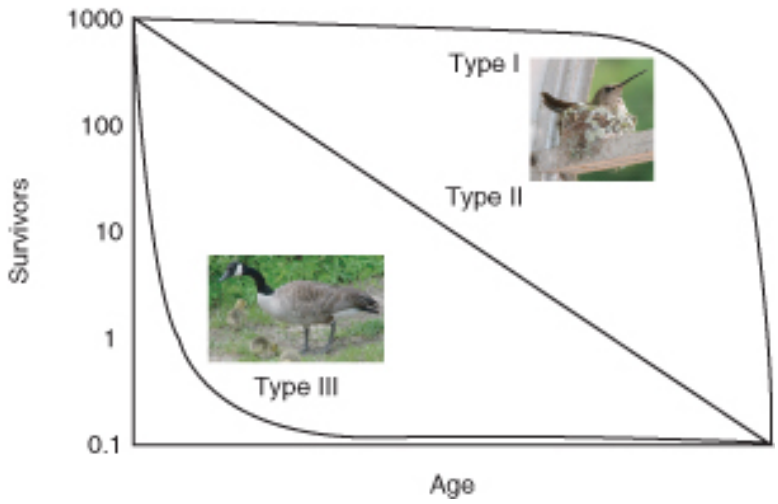

Figure 17.13: Survivorship curves show the various strategies for achieving population growth by adjustments in birth rate and death rate. Recall that Hummingbirds have low birth rates (), but through time and energy spent on parental care and feeding, ensure high survival rates for their altricial offspring (low). Geese, however, invest energy in many large eggs (high) to offset high death rates from predation () among their precocial offspring.

Migration and Other Movements Affect Population Densities

Populations change not only through births and deaths, but also via **immigration**, movement of individuals into a population from other areas, and **emigration**, movement of individuals out of a population. If we add per capita rates of immigration and emigration into our equation for population growth rate, it becomes:

$$r = (b + i) - (d + e)$$

growth rate = (birth rate + immigration rate) – (death rate + emigration rate)

Many kinds of movement adaptations regularly add to or subtract from population density.

- Most species have some means of **dispersal** – movement of offspring away from the parents. This "behavior" reduces competition within the population, promotes colonization of suitable habitat, and improves reproductive success. Some dispersal mechanisms take advantage of natural energy in the environment. For example, dandelion seeds grow "parachutes" which allow wind to carry them far from their parents – and sometimes entirely out of a population (**Figure** 17.14). For the same reason, immobile animals such as corals often produce motile larva. Mobile animals often evolve behaviors which ensure dispersal. A lone gray wolf which leaves its birth pack must find a mate and an unoccupied territory in order to reproduce; within the pack, usually only the alpha male and female have offspring. Dispersal behaviors are common in the

living world; have you - as a teenage high school student, begun to feel stirrings of the wish to leave home?

Figure 17.14: Wind carries dandelion seeds away from their parent plants. The parachute adaptation allows for dispersal, reducing competition within the population and promoting colonization of suitable habitat.

- **Migration**, the direct, often seasonal movement of a species, is a predictable change for some animal populations. Many northern hemisphere birds, such as Swainson's Hawks (**Figure** 17.15), migrate thousands of miles southward in the fall and return north to nest in the spring in order to follow summer's long days which provide extra hunting time and a greater abundance of food.

Apparently, energy benefits outweigh costs for this annual long-distance commute. Elk migrate vertically – up the mountains in spring as snow recedes and down the mountains in fall as winter advances. Monarch butterflies migrate in "shifts"; somewhat like a relay team, successive generations divide the task of moving from Mexican wintering grounds to northern summer habitats. Such migrations do not add to or subtract from populations as much as they move entire populations from one set of boundaries and environmental conditions to another. Some species, such as Peregrine Falcons, have both migratory and non-migratory forms, so their populations may grow or decline with migration. Gray Whales migrate 12,500 miles from Alaska to Mexico for calving, but at least one population limits its northward journey to the Oregon coast (**Figure** 17.16). Seasonal densities of migratory species vary considerably, but resources and environmental benefits vary as well. Migration can affect all four factors of the growth rate equation.

Figure 17.15: Entire populations of Swainson's Hawks migrate annually from North America to South America and back. Migration can affect all four factors of the growth rate equation: rates of birth, death, immigration, and emigration.

Figure 17.16: Gray Whales migrate up to 12,500 miles – further than any other mammal. At least one population stops its northward journey in Oregon; this behavior probably results in immigration and/or emigration, changing intraspecific interactions as populations merge and separate.

Other types of movement are less predictable, but still may affect population growth.

- **Nomadism**, regular, wide-ranging wandering behavior, allows some species to compensate for fluctuating food sources. Normally arctic species, Snowy Owls occasionally venture as far south as Texas, southern Russia, and northern China (**Figure** 17.17). Bohemian waxwings are notoriously nomadic, feeding on highly variable berry supplies.

- **Irruptions** or **invasions** are irregular movements, often caused by food source failures. Owls such as Great Grays and Borealis occasionally invade northern US states from their Canadian homes when rodent populations decline. Some may remain to nest following such an irruption.
- **Range expansion** involves the gradual extension of a population beyond its original boundaries. Recent examples in the US include Cardinals, now common in northern areas where they were originally absent. The Swainson's Thrush follows an indirect and unnecessarily long migration path - retracing, scientists believe, a range expansion from 10,000 years ago. **Intentional introductions** of non-native species such as the House Sparrow and **reintroductions** of extirpated species such as Peregrine Falcons throughout the Eastern US are human-initiated colonizations, which are often followed by range expansions.
- Closely related to range expansion is **colonization**, but the latter often involves newly created, or at least newly found, habitats. Illustrating both range expansion and colonization, the small red-eyed dragonfly spread throughout Europe in the late 20th century and colonized Britain in 1999 (**Figure** 17.18).

Figure 17.17: Normally arctic species, Snowy Owls occasionally wander as far south as Texas, southern Russia, and northern China. This nomadic behavior allows them to feed on prey which have unpredictable fluctuations in population density.

Figure 17.18: Small red-eyed dragonflies expanded their range throughout northwest Europe in the late 20 century and colonized Britain in 1999.

How Do Populations Grow in Nature?

You learned above that populations can grow exponentially if conditions are ideal. While exponential growth occurs when populations move into new or unfilled environments or rebound after catastrophes, most organisms do not live in ideal conditions very long, if at all. Let's look at some data for populations growing under more realistic conditions.

Biologist Georgyi Gause studied the population growth of two species of *Paramecium* in laboratory cultures. Both species grew exponentially at first, as Malthus predicted. However, as each population increased, rates of growth slowed and eventually leveled off. Each species reached a different maximum, due to differences in size of individuals and space and nutrient needs, but both showed the same, S-shaped growth pattern. **Figures** 17.19, 17.20, and 17.21 show this growth pattern graphically as an S-shaped curve.

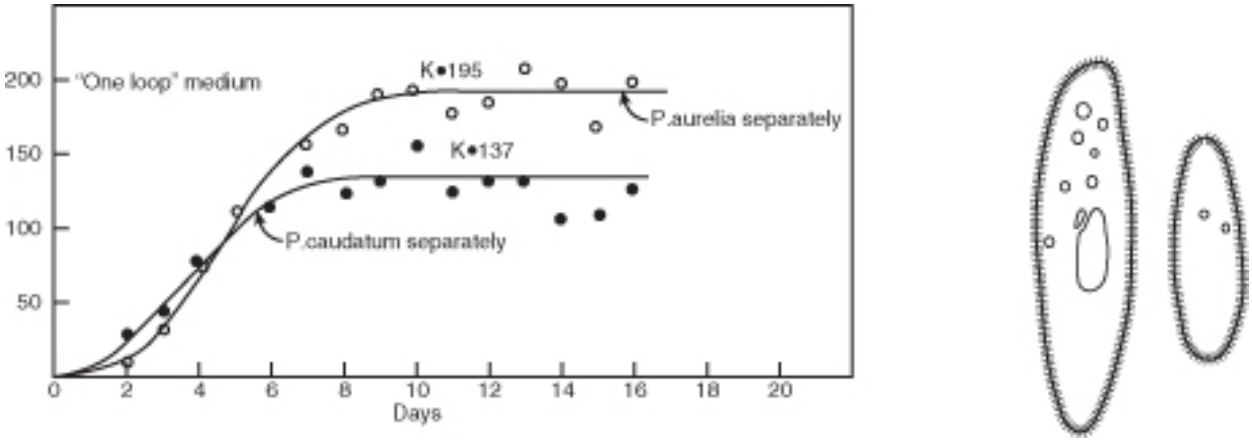

Figure 17.19: Two species of Paramecium illustrate logistic growth, with different plateaus due to differences in size and space and nutrient requirements. The growth pattern resembles and is often called an S-curve. Slow but exponential growth at low densities is followed by faster growth and then leveling.

Perhaps even more realistic is the growth of a sheep population, observed after the introduction of fourteen sheep to the island of Tasmania in 1800. Like the lab *Paramecia*, the sheep population at first grew exponentially. However, over the next 20 years, the population sharply declined by 1/3. Finally, the number of sheep increased slowly to a plateau. The general shape of the growth curve matched the S-shape of Paramecium growth, except that the sheep "overshot" their plateau at first.

As Malthus realized, no population can maintain exponential growth indefinitely. Inevitably, **limiting factors** such as reduced food supply or space lower birth rates, increase death rates, or lead to emigration, and lower the population growth rate. After reading Malthus' work in 1938, Pierre Verhulst derived a mathematical model of population growth which closely matches the S-curves observed under realistic conditions. In this **logistic (S-curve) model**, growth rate is proportional to the size of the population but also to the amount of available

Figure 17.20: Sheep introduced to Tasmania show logistic growth, except that they overshoot their carrying capacity before stabilizing.

resources. At higher population densities, limited resources lead to competition and lower growth rates. Eventually, the growth rate declines to zero and the population becomes stable.

The logistic model describes population growth for many populations in nature. Some, like the sheep in Tasmania, "overshoot" the plateau before stabilizing, and some fluctuate wildly above and below a plateau average. A few may crash and disappear. However, the plateau itself has become a foundational concept in population biology known as **carrying capacity (K)**. Carrying capacity is the maximum population size that a particular environment can support without habitat degradation. Limiting factors determine carrying capacity, and often these interact. In the next section, we will explore in more detail the kinds of factors which restrict populations to specific carrying capacities and some adaptations that limit growth.

Limits to Population Growth

A **limiting factor** is a property of a population's environment – living or nonliving – which controls the process of population growth. Biologists have identified two major types of limiting factors: Density-dependent factors and Density-independent factors.

- **Density-dependent factors** promote **intraspecific competition** – competition between members of the same population for the same resource – as the population grows and becomes more crowded. Density-dependent limiting factors have the potential to control population size. Consider food supply as an example. When population density is low, amount of food per individual is high, and birth rates are high. As density increases, food supply per individual decline and birth rates drop, causing growth rate

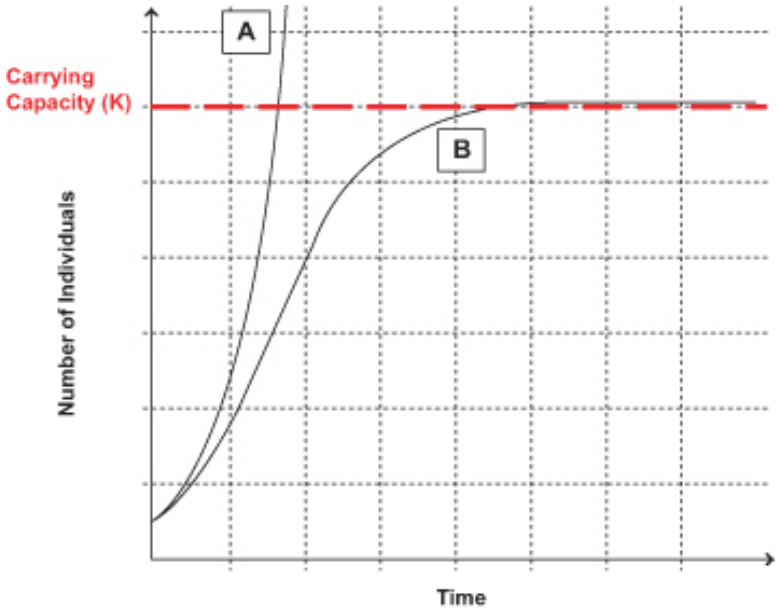

Figure 17.21: Growth of populations according to Malthus' exponential model (A) and Verhulst's logistic model (B). Both models assume that population growth is proportional to population size, but the logistic model also assumes that growth depends on available resources. A models growth under ideal conditions and shows that all populations have a capacity to grow infinitely large. B limits exponential growth to low densities; at higher densities, competition for resources or other limiting factors inevitably cause growth rate to slow to zero. At that point, the population reaches a stable plateau, the carrying capacity (K).

to decline. Eventually, food shortages may lead to increased death rates and a negative growth rate, lowering population size. Lower population size means more food per individual, and the population begins to grow again, reaching or temporarily overshooting the carrying capacity. Food supply in this instance is a regulatory limiting factor, because it keeps the population at equilibrium. Density-dependent limiting factors may include:

- Light
- Water, nutrients/minerals, or oxygen
- Waste, or the ability of an ecosystem to recycle nutrients and/or waste
- Predation by predators which feed preferentially on more abundant prey
- Disease and/or parasites
- Space, with or without territorial behaviors, or nesting sites
- Temperature
- Aggressive behaviors, often combined with stress and effects on immune systems

Let's look at two examples in detail, to emphasize the importance of density-dependent regulation of growth. First, waste products build up with increasing population density. Most environments have some capacity for recycling of wastes, but sometimes rapid population growth means that natural environmental systems can't keep up. An interesting - if not completely natural - example is the growth of yeast populations through fermentation in the making of wine. Alcohol is a waste product for the yeast, even though it is the point of the process as far as we're concerned. As the yeast population grows, alcohol builds up; but alcohol is toxic – to yeast as well as to humans – and after the concentration reaches 13%, increased death rates doom the yeast population. Therefore, no naturally fermented wine contains more than 13% alcohol.

- A second density-dependent limiting factor is predation. Predators kill and eat their prey, of course, so predation increases prey death rate and can cause negative growth rates – population decline. If predators have multiple types of prey, and switch their feeding to specific prey only when they are abundant, predators may regulate prey population size. However, especially in northern climates, predators often specialize on a single prey species. Goshawks, for example, feed primarily on ruffed grouse, and Canada Lynx depend on snowshoe hares (**Figure** 17.22). If predation causes a significant decline in the prey population, starving predators may experience their own (delayed) decrease in population as a result of lower birth rates or increased death rates. The result is a **predator-prey cycle**; both populations rise and fall, with predator populations trailing prey (**Figure** 17.23).

Goshawks play the game with a little twist; when ruffed grouse populations in their Canadian conifer forest homes decline, they migrate southward. Grouse populations show ten-year cycles; note that the goshawk counts from Hawk Ridge in Duluth, Minnesota show ten-year "invasions" which correspond to prey population lows in Canada (**Figure** 17.24).

Figure 17.22: Populations of snowshoe hare (left) and their Canada Lynx predator (right) show repeating cycles, with predator population changes trailing those of their prey.

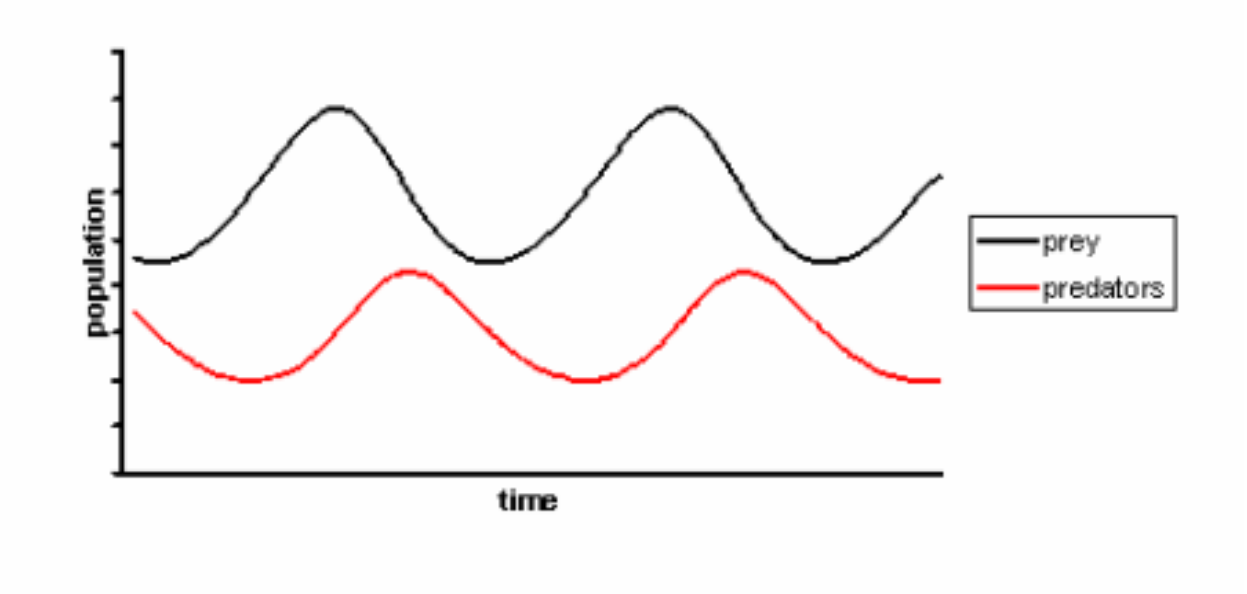

Figure 17.23: Repeating cycles of growth and decline characterize population dynamic interactions between some pairs of predator and prey species.

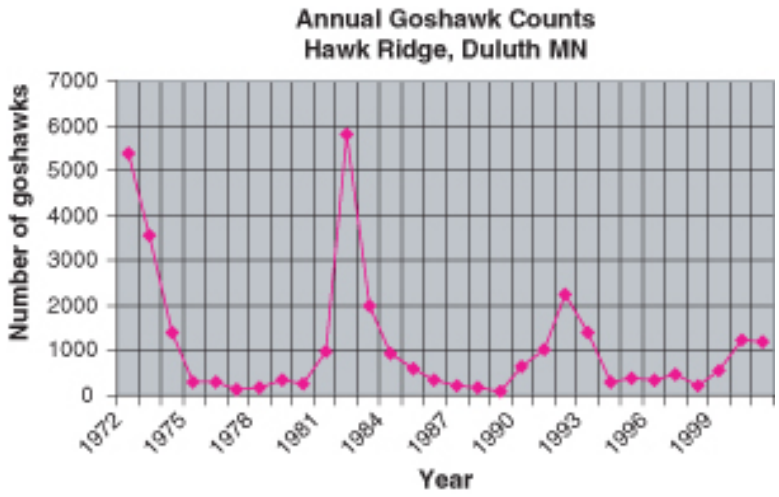

Figure 17.24: The pattern of migration of goshawks observed at Hawk Ridge in Duluth, Minnesota, shows irruptions which correspond to low points in cycles of their Canadian prey populations (ruffed grouse). Such cycles are the result of density-dependent interactions between predator and prey. Predators cause increased death rates in prey populations, especially at high prey densities. When prey populations crash as a result of predation, predators are stressed and some (such as lynx) decline. Others, such as the goshawk, irrupt southward in search of higher-density populations.

All of these factors have the potential to lower birth rates or increase death/emigration rates via increased intraspecific competition at higher population densities. Many natural populations are kept at or below carrying capacity by one or a complex interaction among several of the above limiting factors.

- **Density-independent factors** can also limit populations, but they seldom regulate populations because they act irregularly, regardless of the population's density. Populations limited by density-independent factors seldom reach carrying capacity. Weather is a good example. Agaves (Century Plants) reproduce once at the end of a long lifespan (**Figure** 17.25). The average lifespan is about 25 years rather than a full century, but an individual's lifespan depends at least in part on erratic rainfall. Agaves will reproduce only after rainfall allows sufficient growth – however long that takes. Eventually, a wet season will bring about a single episode of flowering and the production of a huge number of seeds. Their growth and eventual reproduction will, in turn, depend on erratic rainfall. The density-independent factor rainfall limits birth rate, which in turn limits growth rate, but because of its unpredictability, it cannot regulate Agave populations.

Other density-independent limiting factors include human activities:

Figure 17.25: Each Century Plant reproduces only once during its long lifespan. This strategy allows it to gather sufficient water over a number of years in an environment where rainfall is scarce and unpredictable. Then, during an especially wet season, the plant produces a huge number of seeds and dies. Does the Century Plant's pattern remind you of the salmon's life cycle?

- *Pesticides and herbicides*: For example, DDT thinned the eggshells of Peregrine Falcons, reducing their birthrates and leading to their extirpation from the eastern half of North America.
- *Habitat destruction*: Conversion of prairies and grasslands worldwide drastically reduced populations of Burrowing Owls in North America and Giant Pandas in China.

To conclude our discussion of population dynamics, let's look at two sets of adaptations related to the logistic growth curve which describe the growth of most populations. These should remind you of the survival patterns we discussed earlier in this lesson. Recall that for logistic growth, $\boldsymbol{r}$ is the **growth rate** of the population, and $\boldsymbol{K}$ is the **carrying capacity**.

- Scientists have found that species adapted to unstable or unpredictable environments are usually limited by density-independent factors to population densities considerably lower than carrying capacity. Such environments favor adaptations which maximize growth rates: early maturity, small size, high numbers of small offspring, single episodes of reproduction, short life expectancy, and the ability to disperse widely. Because populations are usually far below carrying capacity, crowding is minimal, so these species invest little energy in competitive adaptations. Survivorship curves (**Figure** 17.13) are Type III, with high early death rates. Such species are said to be **r-selected** – that is, selected for rapid growth. Weed species are often *r*-selected for colonization and rapid population of disturbed or newly created habitats such as roadsides, abandoned fields, mudslides, or lava flows. Jack pine trees are *r*-selected species which "pioneer" clear areas immediately after forest fires. They grow quickly in hot, dry soils and release seeds from cones which are opened only by fire – reproducing and dispersing seeds at just the right, if unpredictable, time (**Figure** 17.26).

- Whereas density-independent factors limit **r-selected species** in unpredictable environments, **K-selected species** are adapted to stable environments and regulated by density-dependent factors. Stable environments support K-selected populations at or near carrying capacity, at which point crowding leads to significant intraspecific competition. Such environments favor adaptations for efficient resource utilization which confer competitive ability. K-selected individuals often grow slowly to large size, live long, and delay but repeat reproduction of fewer offspring. They may provide extensive parental care because they can count on environmental stability and survival of these relatively few offspring. Survivorship curves resemble the Type I pattern: long life expectancy and relatively low death rates in the stable environment. Maple trees are K-selected "climax" species which grow slowly in their own shade and reproduce relatively large seeds over a number of years throughout their relatively long lifespan (**Figure** 17.27).

Characteristics of r-selected and K-selected species are compared in **Table** 17.3.

Figure 17.26: Jack pines show r-selected adaptations to an unpredictable (density-independent) limiting factor: fire. Cones (bottom image) open to release many tiny seeds only at high temperatures. The trees (top image) grow quickly in the open, bare areas left by forest fires, so are often called "pioneer" species.

Figure 17.27: Maple trees show K-selected adaptations to a predictable shade environment they help to create. Maples release relatively large seeds annually, and offspring grow slowly but steadily in the shaded, rich soil of their parents. Maples experience significant intraspecific competition, and their populations tend to be limited by density-dependent factors. Because maple forests tend to persist for long periods because they can grow in their own shade, they are often called "climax" species.

Table 17.3:

	r- Selected Species	K-Selected Species
Environment	Unstable	Stable
Type of Regulating Factors	Density-independent	Density-dependent
Organism Size	Small	Large
Maturity	Early	Late
Number of Offspring	Many	Few
Energy used to make each Individual	Low	High
Average Life Expectancy	Short	Long
Number of Reproductive Events per Individual	Once	Many times
Survivorship	Type III: only a few individuals live long lives	Type I or II: most individuals live long lives

In conclusion, all populations eventually reach limits, at or below carrying capacities for the ecosystems in which they live. Some have adaptations for rapid growth, but the unpredictable environments in which they live inflict high death rates. Others live in stable environments where death rates are relatively low, but their populations are high, so individuals must spend energy on costly competitive strategies in order to gather scarce sunlight, nutrients, or water - or fight disease or predation. Many species live between these extremes, but all populations have limits.

Lesson Summary

- The ways in which populations change are called population dynamics.

1. Populations have the potential to grow exponentially, at least under ideal conditions.
2. Exponential growth begins with slow growth, but as population increases, growth rate increases.
3. J-curves depict the pattern of exponential population growth.
4. Malthus first described exponential growth for the human population and predicted that humans would outgrow their food resources, leading to widespread famine or war.

- If birth rate (plus immigration) exceeds death rate (plus emigration), a population grows. If death rate exceeds birth rate, the population declines. And if birth rate and death rate are in equilibrium, growth rate is zero and the population remains stable.

- In a stable population, each individual (on the average) produces one offspring which survives long enough to reproduce itself.
- *Altricial* species have a few undeveloped offspring but invest a great deal of energy in parental care. *Precocial* species invest energy in a large number of well-developed offspring, but little in parental care.
- The earlier species begin to reproduce, the faster their population grows, with all other factors being equal.

- Dispersal moves offspring away from parents, reducing intraspecific competition.
- Migration, seasonal movement of populations, can affect all four components of population growth rate.
- Regular wandering behavior (nomadism) adapts specific populations to fluctuating food supplies.
- Irruption, range expansion, and colonization have irregular, unpredictable effects on population growth.

- Few populations in nature grow exponentially. No population can continue such growth indefinitely.
- The logistic (S-curve) model best describes the growth of many populations in nature.
- In the logistic model, growth rate depends on both population size and availability of resources. Growth is slow at first, but as size increases, growth accelerates. At higher densities, limited resources cause growth rate to decline, and populations stabilize at carrying capacity.

- A limiting factor is a property of a population's environment which restricts population growth.
- Density-dependent limiting factors lower birth rates or increase death/emigration rates via increased intraspecific competition at higher population densities.
- Many natural populations are kept at or below carrying capacity by one or a complex interaction among several density-dependent limiting factors, such as competition, predation, or disease.
- Density-independent factors, such as rainfall, drought, or pollution, can also limit populations, but they seldom regulate populations because they act irregularly, regardless of the population's density.
- Cycles of growth and decline limit some predator and prey populations.
- Density-independent factors limit *r*-selected species in unpredictable environments, while K-selected species are adapted to stable environments and regulated by density-dependent factors.

Review Questions

1. Explain Malthus' ideas about population growth and their significance to evolutionary theory.
2. Compare exponential(J-curve)growth to logistic(S-curve)growth, and explain the conditions under which each occurs in nature.
3. Summarize the equation for population growth rate, and explain each factor.
4. Compare survival and reproduction in *altricial* species to the same factors for *precocial* species.
5. How might delaying age of childbirth prevent the need to limit family size, as China has done?
6. Give examples of dispersal and migration, and how they affect populations.
7. Define carrying capacity and explain its importance to population growth.
8. Compare and contrast density-dependent and density-independent limiting factors.
9. Relate predator-prey cycles to density-dependent population control.
10. Compare and contrast the adaptations and environmental characteristics typical of r-selected species to those of K-selected species.

Further Reading / Supplemental Links

- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookpopecol.html
- http://www.geography.learnontheinternet.co.uk/topics/popn1.html
- http://curriculum.calstatela.edu/courses/builders/lessons/less/biomes/breeding.html
- http://www.bestfootforward.com/
- http://www.footprintnetwork.org/gfn_sub.php?content=footprint_overview
- http://www.panda.org/news_facts/publications/living_planet_report/index.cfm
- http://www.worldchanging.com/archives/006904.html
- http://lca.jrc.ec.europa.eu/lcainfohub/introduction.vm
- http://www.ilea.org/leaf/richard2002.html

Vocabulary

altricial Refers to a pattern of growth and development in organisms which are incapable of moving around on their own soon after hatching or being born.

birth rate (b) Number of births within a population or subgroup per unit time; in human demography, the number of childbirths per 1000 people per year.

carrying capacity (k) The maximum population size that a particular environment can support without habitat degradation.

colonization Movement of a population into a newly created or newly found area.

death rate (*d*) Number of deaths within a population or subgroup per unit time; in human demography, the number of deaths per 1000 people per year.

density-dependent factor Factor which has the potential to control population size because its effects are proportional to population density.

density-independent factor Factor which may affect population size or density but cannot control it.

dispersal Movement of offspring away from parents, resulting in reduced competition within the population and more effective colonization of suitable habitat.

emigration (*e*) Movement of individuals out of a population's range.

exponential model (geometric or J-curve) A model of population growth which assumes that growth rate increases as population size increases.

immigration (*i*) Movement of individuals into a population's range from other areas.

intraspecific competition Competition between members of the same population for the same resource.

irruption (invasion) Irregular movements, often caused by food source failures.

K-selected species A species which has adaptations which maximize efficient utilization of resources, conferring competitive strength near or at carrying capacity.

limiting factor A property of a population's environment – living or nonliving – which controls the process of population growth.

logistic (S-curve) A model of population growth which assumes that the rate of growth is proportional to both population size and availability of resources.

migration The direct, often seasonal movement of a species or population.

nomadism Regular, wide-ranging wandering behavior, which allows some species to compensate for fluctuating food supplies.

population A group of organisms of a single species living within a certain area.

population dynamics Changes in population size and structure.

population growth rate (r) The change in population size per member of the population per unit time.

precocial Refers to species in which the young are relatively mature and mobile from the moment of birth or hatching.

predator-prey cycle Regular, repeating increases and decreases in a prey population followed by corresponding changes in its predator's population.

r-selected species Species which has adaptations which maximize growth rate, r.

range expansion The gradual extension of a population beyond its original boundaries.

Points to Consider

- Why do you think Malthus' predictions of widespread famine and war have not (yet?) been realized? Do you think his ideas make sense for the future?
- Are humans altricial or precocial? Why?
- In your opinion, could delaying age of first childbirth help solve human population problems?
- How important do you think dispersal, range expansion, or immigration are for human populations?
- Do you think humans have more r-selected adaptations, or K-selected adaptations?
- Do you think Earth has a carrying capacity for humans? If so, what kinds of limiting factors determine that carrying capacity?

17.3 Lesson 17.3: Human Population Growth: Doomsday, Cornucopia, or Somewhere in Between?

Lesson Objectives

- Contrast the Neo-Malthusian or "limits to growth" and cornucopian or "technological fix" views of human population growth.
- Compare the overall pattern of human population growth to the J-curve (exponential) and S-curve (logistic) models.

- Analyze the factors which have influenced human population growth from our beginnings 200,000 years ago to 1804, when we first reached the one billion mark.
- Describe the four stages of human population growth as outlined by the demographic transition model.
- Evaluate the demographic transition model as it applies to European population growth in the late 18th and 19th centuries.
- Evaluate the demographic transition model as it applies to less developed countries.
- Apply the demographic transition model to recent changes in developed countries.
- Using age-sex structures, contrast population growth in developed countries to growth in undeveloped countries.
- Explain the concept of replacement fertility rate.
- Discuss the implications of Stage 5 population dynamics.
- Know and understand predictions for future worldwide human population growth.
- Analyze limiting factors and technological advances which may contribute to a carrying capacity of Earth for the human population.
- Explore the concept of sustainability as a goal for economic, social, and environmental decision-making.
- Explain the tool of ecological footprint analysis as a means of evaluating the sustainability of lifestyles for individuals, countries and the world.
- Calculate your ecological footprint and compare it to averages for your country and the world.
- Recognize our human potential to make decisions which could direct future population growth.
- Explore some options for social, political and cultural change, and environmental conservation which could help to balance population dynamics and resource utilization.

Introduction

Hundreds of stone figures measuring up to 10 meters tall and weighing up to 87 tons overlook a low-diversity grassland on Easter Island in the Pacific Ocean (**Figure** 17.28). The food sources, woody trees, and rope-yielding plants which helped to build and transport these statues over five hundred years ago are gone.

Pollen analyses suggest that the island was totally forested at least until 1200 CE, but that by 1650 the forests had entirely disappeared. Middens (waste dump sites) show a sudden disappearance of sea bird and fish bones, suggesting that wood for canoes was no longer available. Sediments reveal that half of native plant species had become extinct. Later fire pits indicate the possibility of cannibalism.

Jared Diamond, in his book *Collapse: How Societies Choose to Fail or Succeed,* examines this bleak scene and other past societies and concludes that doomed civilizations share eight traits which contribute to their collapse. Seven of the eight traits are rooted in overpopulation relative to environmental carrying capacity. Diamond considers Easter Island to

Figure 17.28: Easter Island today is a low-diversity grassland nearly devoid of the food sources, woody trees, and rope-yielding plants which helped to build and transport these 10-meter stone statues. Jared Diamond suggests that overpopulation and overexploitation of resources led to the collapse of a once-thriving Easter Island society, and that Easter Island is "Earth writ small" – a warning to the world.

be "Earth writ small" – a warning that this island's environmental devastation could foreshadow a similar fate for our planet. He encourages humans to learn from earlier collapses to conserve the forest, soil, water, animal, fish, photosynthetic, atmospheric, and energy resources upon which our human lives depend. A large group of people sometimes known as **"Neo-Malthusians"** join Diamond in his belief that human population growth cannot continue without dire consequences.

Julian Simon and a group dubbed **"cornucopians"** see the human condition differently. Named for the mythical Greek "horn of plenty" which supplied endless food and drink magically, cornucopians believe that the Earth can provide an almost limitless abundance of natural resources, that few natural limits to growth exist, and that technology can solve or overcome population-induced resource scarcity and environmental degradation. Larger human population (within an appropriate political environment) is the answer to the problems of population growth, according to Simon.

Are you, like Diamond and Malthus before him, a "doomster"? Or do you join Simon as a "boomster"? Most "doomsters" and "boomsters" share the belief that we are responsible for managing problems related to population growth. Let's use our understanding of **population** biology to study the human population. Our goal will be to shed light on the decisions we – the only species able to consider and alter our rates of birth and death – make about future population growth.

The past two lessons have shown how populations in nature grow. You have learned that all

populations have the *potential* to grow **exponentially** (**J-curve** pattern of growth), but that exponential growth is limited to ideal conditions, which are rare in nature. In nature, competition for limited resources or unpredictable, density-independent limiting factors restrict populations to densities at or below carrying capacities (**S-curve** growth pattern). Some populations grow smoothly to a stable carrying capacity, but others overshoot that density and may crash before rebuilding to a relatively stable level. A few crash to extinction. In unstable environments, some populations establish cycles of population growth and decline. Unstable environments favor adaptations for rapid growth (**r-selected species**), and stable environments favor adaptations for efficient use of resources (**K-selected species**).

Where do humans fit? Are we built for growth – or conditioned for efficient use of resources? Does our growth pattern resemble a J, or an S? Are we in danger of extinction? What exactly is our "population problem," and what can we do to solve it?

Early Human Population Growth

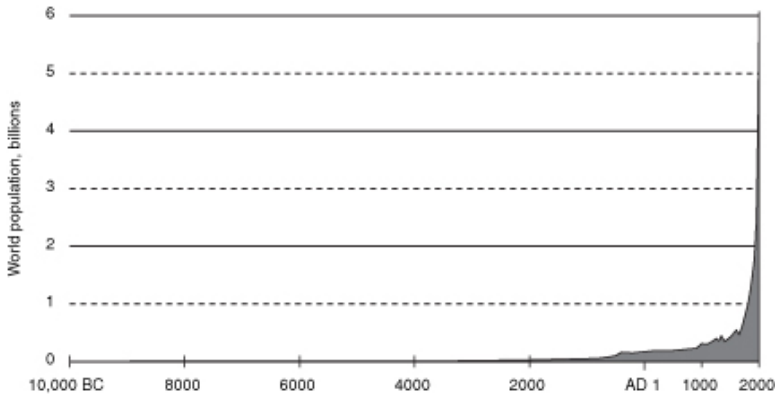

Figure 17.29: The growth of the world's human population (using estimates by scholars in the field for the time before census data) shows a classic J shape on this 12,000-year scale. Can you distinguish the decline due to "black death" in the early middle ages?

Let's begin by looking at the data. Worldwide human population from 10,000 BCE through today is graphed in **Figure** 17.29. The theoretical J (exponential) and **S (logistic) growth** curves are reviewed in **Figure** 17.30. Overall, our growth resembles exponential growth (the J curve), increasing very slowly at first, but later growing at accelerating rates which show no sign of nearing carrying capacity. We appear to be *r*-selected for rapid growth; indeed, some have described humans as the most successful "weed species" Earth has ever seen as we are fast growing, rapidly dispersing, and colonize habitats from pole to pole. If Earth has a carrying capacity for humans, it is not yet visible in our growth curve – at least on this scale.

However, closer study of human population dynamics reveals more complexity. Different countries show different patterns of population growth today, and history shows varying

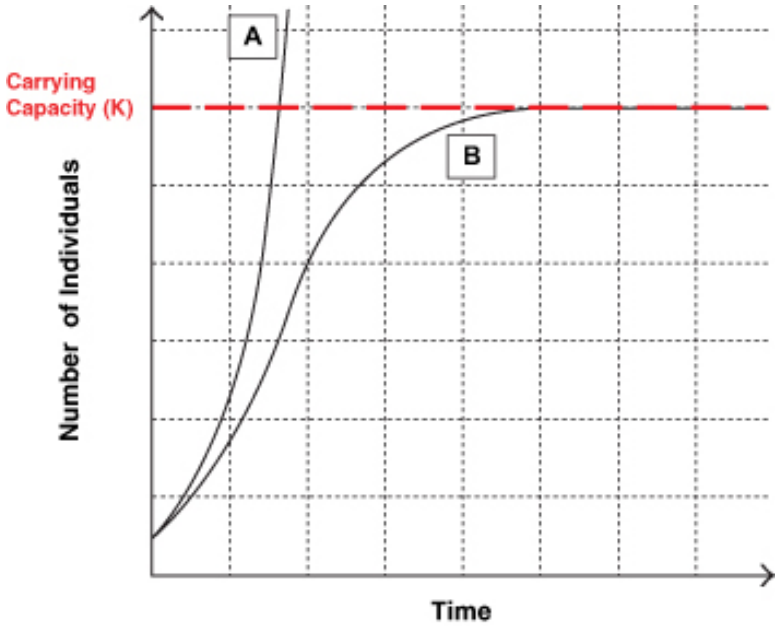

Figure 17.30: Growth of populations according to Malthus' exponential model (A) and Verhulst's logistic model (B). Both models assume that population growth is proportional to population size, but the logistic model also assumes that growth depends on available resources. A model's growth under ideal conditions shows that all populations have a capacity to grow infinitely large. B limits exponential growth to low densities; at higher densities, competition for resources or other limiting factors inevitably cause growth rate to slow to zero. At that point, the population reaches a stable plateau, or the .

patterns of growth across time. The history of human population growth can be divided into four stages. Today's countries show snapshot views of these stages. In this section, we will look at early human population growth.

As scientists currently understand human history, *Homo sapiens* arose about 200,000 years ago in Africa. Living as nomadic hunter-gatherers, we migrated to Eurasia and Australia about 40,000 years ago and into the Americas 30,000 years later. Throughout this period, both birth rates and death rates were probably high – as much as 5%. Our human population grew slowly as we spread throughout the world, out-competing other hominid species with our apparently superior reproductive and competitive adaptations. Ice ages, warming periods, and volcanic eruptions were density-independent factors which severely limited our population growth. For example, a "supervolcanic" eruption at Toba in Sumatra 74,000 years ago covered India and Pakistan with more than 5 feet of ash, causing 6 years of nuclear winter, a thousand-year ice age, and the death of up to 99% of the humans living at the time!

With the invention of agriculture 10,000 years ago, we began to develop settled civilizations and trade. Disease associated with animal domestication and city living increased death rates, but reliable food supplies, shared childcare, and division of labor increased birth rates. These effects may have offset each other; slow and uneven growth probably continued. However, the development of agriculture, like many advances in technology, almost certainly raised carrying capacity.

Beginning about 6000 years ago, political states evolved, cooperated or competed, and sometimes waged war. Empires formed, connecting previously independent populations. In the Middle Ages, technology advanced, and the 17th century brought the Scientific Revolution. Throughout this long period of human history, death rates and birth rates continued to be high. **Density-independent factors** such as drought and the "little ice age" combined with **density-dependent factors** such as disease to keep death rates high and variable. The "black death" of the mid-fourteenth century killed as many as 75 million people worldwide and the disease is one of the very few events whose effects are visible in any graph of human population growth (**Figures** 17.29, 17.31). Birth rates continued at a high level throughout early human history. Carrying capacity rose with major advances in technology, as humans modified the environment by irrigating land, building cities, and transporting animals, plants, and products. The overall result was slow growth and a young population. By 1804 CE, the world's human population had reached 1 billion.

Demographic Transition

Major changes in human population growth began during the 18th century, but they affected different regions at different times. We will first consider Europe, and later compare Europe to other regions of the world. In 18th century Europe, seed planters, improved ploughs, threshing machines, crop rotation, and selective breeding of animals led to major growth in

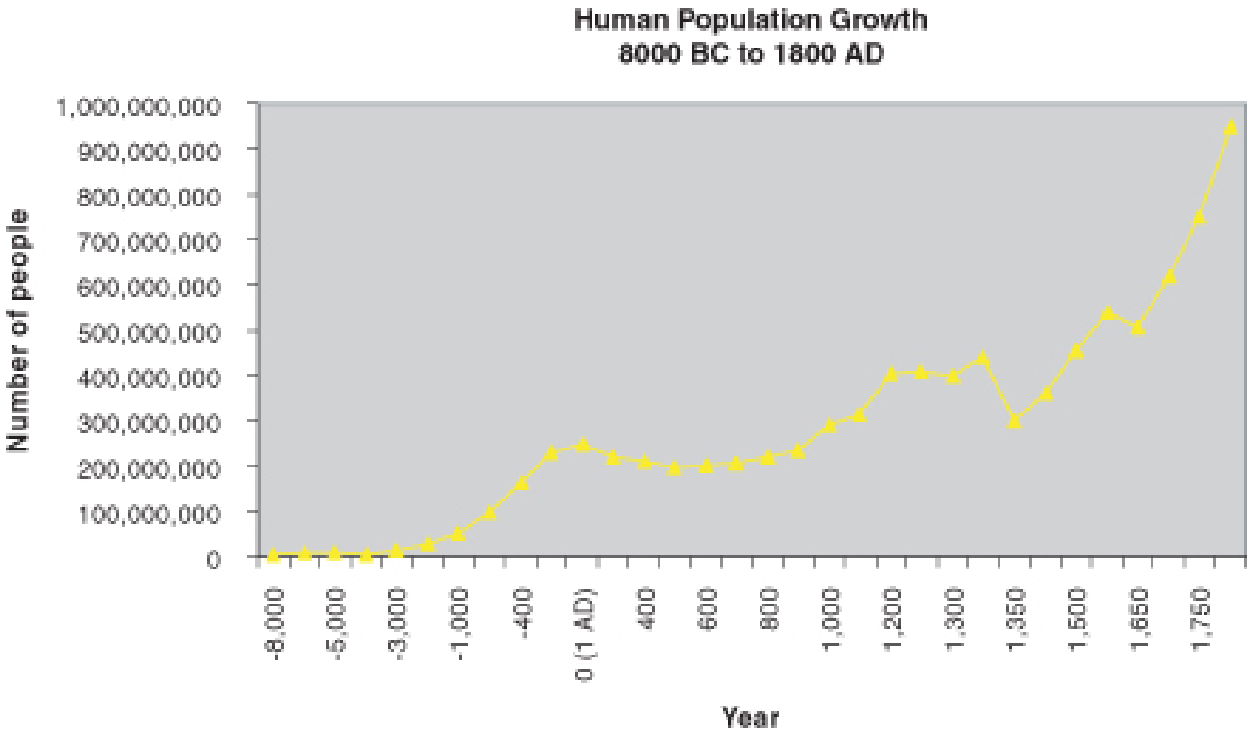

Figure 17.31: Early human populations showed slow, uneven growth. At this scale, the negative effect of increased death rate due to the "black plague" during the mid-fourteenth century is clear.

food supplies, so death rates due to starvation declined. With increasing understanding of the causes of disease, people improved water supplies, sewers, and personal hygiene – and lowered death rates even more. The Industrial Revolution of the 19th century developed new sources of energy, such as coal and electricity. These further increased the efficiency of new agricultural machines and promoted the development of new forms of transportation, mainly railroads, which improved distribution of food. Death rates fell – particularly for those 5 to 10 years of age, allowing many more children to survive to reproduce. The pattern of human survivorship shifted toward a Type III curve.

Although death rates fell, birth rates remained at earlier levels. The gap between birth and death rates increased, and population growth began to accelerate (remember that $r = b - d$). Although this change did not happen uniformly throughout the world, it was soon reflected in world population levels: it took 200,000 years for the human population to grow to 1 billion, but only 123 years to grow to 2 billion!

Demographic transition theory holds that human populations pass through four stages of growth (**Figure** 17.32).

Figure 17.32: Demographic transition theory proposes that human populations pass through four or five predictable stages of population growth. The 1st and 4th stages are relatively stable, in the first stage because b and d are both high, and in the last because b and d are both low. The key to the theory (disputed by some) is this: once death rates fall due to industrialization and technology, birth rates will follow (the Transition, Stages 2 and 3). Because the theory is based on observations of developed countries, some people dispute its universality.

- Early human history, with its slow, uneven growth maintained by high rates of birth

and death, illustrates Stage 1 (**Figure** 17.31, but compare to section "1" of **Figure** 17.32).

- Stage 2, just discussed for Europe, involves a significant drop in death rate *not matched by an increase in birth rate*, resulting in an increasingly rapid rise in population – exponential growth.
- In Stage 3, according to the theory, changes in technology and society lead to a decline in birth rate:

1. The decline in child mortality and improvement in agriculture leads rural families to realize they no longer need to have as many children.
2. Agricultural improvements shift more people to urban areas and reduce the need for children.
3. Compulsory education removes children from the work force but adds to the cost of raising them.
4. Increasing education and employment of women reduces their time for and interest in having children.
5. Birth control methods expand.
6. Later marriage and delayed childbearing further lower birth rate.

Eventually, according to demographic transition theory, falling birth rates approach already-diminished death rates, and population growth begins to level off.

- In Stage 4, birth rates equal death rates, r = zero, and populations become stable.

This somewhat idealistic theory suggests that societies pass through predictable changes which lead to population growth patterns resembling the logistic or S curve. As we have seen (Figure 1), world population growth does not (yet?) show Stages 3 or 4. However, individual countries appear to be at different stages along the continuum; some have reached Stage 4 and a few even require the addition of a 5th stage.

Recent Population Growth

Death rates have fallen throughout the world, so that no country today is considered to remain in Stage 1. Countries appear to vary with respect to the timing of Stages 2 and 3. Many less developed countries remain in Stage 2, including Yemen, Afghanistan, Bhutan, Laos, and part of Sub-Saharan Africa.

Angola's age structure (**Figure** 17.33) reveals accelerating Stage 2 growth. Widest at its base, the structure indicates many youths who will survive to reproduce at their parents' high **fertility** rates because death rates are declining. Some countries, particularly those in regions of Africa which have been devastated by AIDS, appear stalled in Stage 2 due

to disease and stagnant development. The demographic transition model may not prove to fit population growth in developing countries. Poor, low-income people in undeveloped countries have the highest birth rates. If demographic transition requires wealth and education, the world's unequal distribution of development and resources may mean that these high birth rates will merely maintain exponential growth, rather than precipitate the social change associated with industrialization.

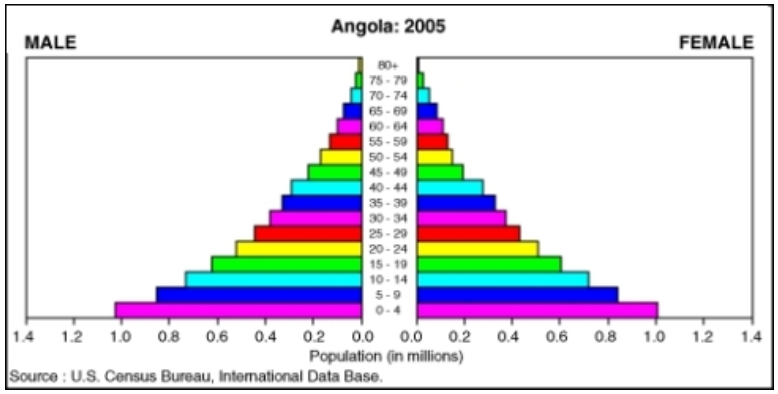

Figure 17.33: Angola's population pyramid reflects Stage 2 growth: The wide bars at its base show the many youths who will survive to reproduce at their parent's high fertility rates because death rates (small steps moving up the pyramid) are declining.

However, many countries appear to have begun the shift to Stage 3. Fertility rates have dropped 40% throughout much of South America, the Middle East, and the Pacific Islands. Countries such as India, Bangladesh, and Zimbabwe have lowered birth rates between 25-40%, and others such as Pakistan, Saudi Arabia, and Haiti have reduced fertility to 10-25% of earlier rates. Populations in most of these countries are beginning to level off, although resistance to change in the social factors which reduce birthrate may delay or prevent this response. Ecologist Garrett Hardin has pointed out that voluntary birth control selects against people who use it; by itself, voluntary control is unlikely to limit population growth.

High levels of industrialization and development have led to **replacement** (or lower) **fertility rates** in most of Europe, the United States, Canada, Australia, Brazil, China, and Thailand. China, Brazil, and Thailand passed through demographic transition extremely rapidly due to rapid economic and social changes. Replacement fertility includes 2 children to replace parents and a fraction of a child to make up for early mortality and at-birth sex ratio differences. Because mortality rates vary, replacement fertility rate ranges from 2.5 to 3.3 in poor countries, but averages 2.1 in developed countries. Globally, replacement fertility is 2.33 children per woman. In Stage 3 countries, populations will eventually stabilize if replacement fertility continues. However, many - including the US – continue to grow rapidly due to the "youth bulges" of exponential Stage 2 growth. The age structures of China and the US (**Figure** 17.34) show demographic transition, but also youth bulges which will mean continuing growth for some time.

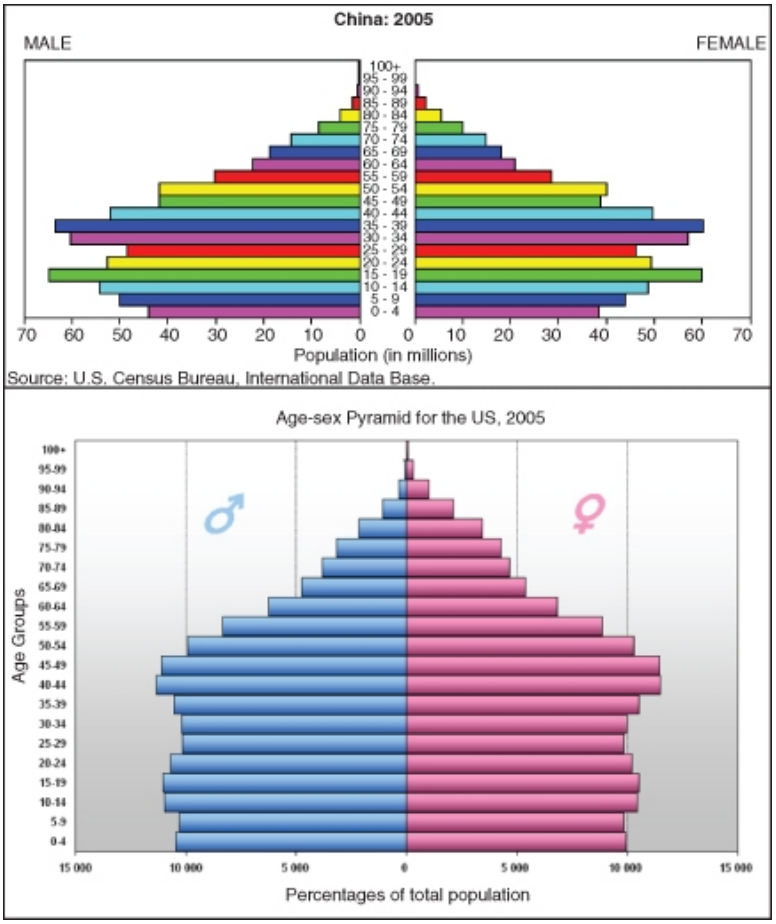

Figure 17.34: Population pyramids for China (above) and the U.S. (below) show decreased birth rates which suggest they have reached Stage 3 of the demographic transition model. Both countries show a population bulge remaining from Stage 2 exponential growth, so populations will continue to grow for a number of years. Eventually, if birth rates remain at replacement levels, populations will stabilize in Stage 4.

Some countries have lowered birthrates below death rates so that r is actually negative. Japan, Germany, Italy, Spain, Portugal, and Greece are not producing enough children to replace their parents; populations in some of the southern European countries have already begun to decline. Top-heavy age structures for Spain and Japan are shown in **Figure** 17.35. In countries such as Russia, negative growth emerged suddenly from economic and political crises which caused emigration, declining fertility, and increased male mortality, rather than from development and wealth as the transition model predicts. Negative growth rates pose economic threats: growth-dependent industries decline, and the burden of a large aging, economically dependent population falls on a smaller group of young workers. These shrinking population conditions are sometimes referred to as **Stage 5** of the demographic transition.

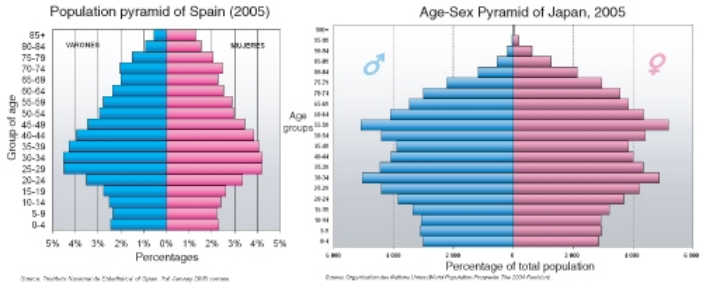

Figure 17.35: The top-heavy age structures for Spain and Japan show declining populations due to birth rates which have fallen below already-low death rates. Unless significant immigration occurs, these countries may suffer negative economic effects, such as decline in growth-dependent industries. The burden of a large aging, economically dependent population may fall on a smaller group of young workers.

Future Population Growth: Does Earth Have a Carrying Capacity for Humans?

As of September 2007, the world's human population stood at about 6.7 billion, growing by 211,090 people each day. Historically, we didn't hit the one-billion mark until 1804 (having begun 200,000 years earlier), but we needed just 12 years to grow by our last billion. Projections by the United Nations and the U.S. Census Bureau predict that by 2050, Earth will host 9.4 billion people; other estimates project that the earth will host 10 to 11 billion people by 2050. See http://www.youtube.com/watch?v=4BbkQiQyaYc or click on the following *World Population* video .

Cornucopians welcome such growth, believing more people are better for technology and innovation. The demographic transition model predicts that when all nations are industrialized, the human population will eventually reach a stable level – a carrying capacity of sorts.

Figure 17.36: A graphic description of world population growth from 1 A.D. World Population (Millenium Edition) was produced and copyrighted by Population Connection (formerly Zero Population Growth, Inc.) in 2000. Population Connection is a nonprofit, 501(c)(3) organization. www.popconnect.org (Watch on Youtube)

However, many scientists believe that humans have already overshot the carrying capacity of Earth for our unique levels of resource exploitation and habitat alteration. They and other Neo-Malthusians predict that resource depletion and environmental degradation will eventually lead to famine, epidemics, or war – a Malthusian crisis.

Does Earth have a carrying capacity for humans? Recall that carrying capacity is the maximum population size that a particular environment can support without habitat degradation. Ideally, carrying capacity matches population size to resource availability. Although the human population is clearly continuing to grow, many scientists believe that we over-consume resources and exceed the environment's capacity to cycle nutrients and process waste. They believe that multiple factors will contribute to a crisis in which disease, starvation, or global conflict will cause a population crash or even extinction:

- Our current *agricultural system*, globally transformed by the **Green Revolution** of the mid-20th century, depends heavily on nonrenewable fossil fuels for fertilizers, pesticides, and irrigation. Ecologist and agriculturalist David Pimentel predicts that to avert disaster, the U.S. must reduce its population to a maximum of 200 million (we are now above 300 million – see the "pop clock" **Figure** 17.37), and the world population must drop to 1/3 its current level. Distribution of food has long been a problem and today has some rather ironic consequences: A 2006 MSNBC report claimed, "There are an estimated 800 million undernourished people and more than a billion considered overweight worldwide."

- Both developing and developed countries depend almost entirely on *petroleum* to fuel industrialization and transportation, as well as agriculture. In 1956, geophysicist Marion Hubbert predicted that world oil production would peak about half a century

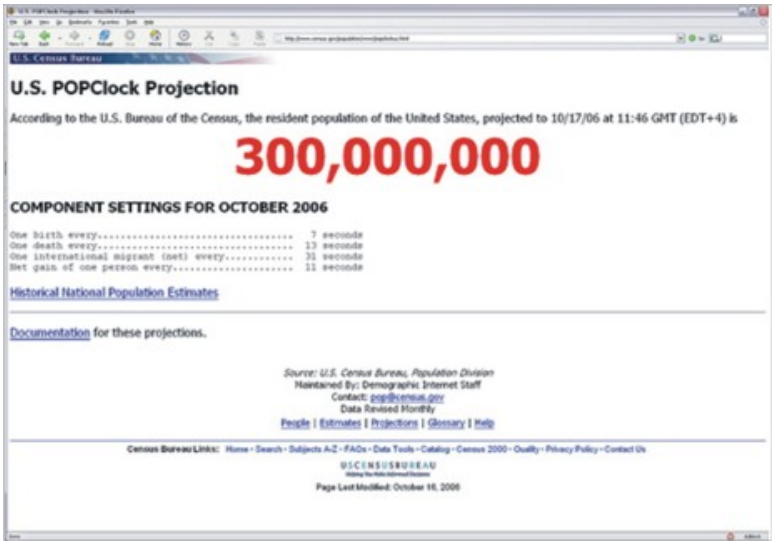

Figure 17.37: The U.S. population passed 300 million on October 17, 2006. Agriculturalist David Pimentel believes the U.S. must lower its population by 1/3 to prevent a crisis caused by inability to continue our fossil fuel-dependent agricultural practices. U.S. and World Population Clocks are maintained by the U.S. Census Bureau online at:

into the future and then decline, initiating a global crisis. Predictions about the consequences of **Peak Oil** range from successful development of alternative fuels, to collapse of the global industrialized economy, to intense nationalism and war. Some analysts, such as energy banker Matthew Simmons, believe that the Peak has already occurred (**Figure** 17.38). Others, like energy industry consultants Wood McKenzie, believe we will not reach the peak for another ten years. The difference does not seem significant, but ten years would allow more time for development of alternative fuels and institution of conservation measures.

- **Fresh water supplies** are declining due to pollution and overuse. According to the United Nations, 2.6 billion people lack water for sanitation, and 1.1 billion have inadequate supplies of safe drinking water. Irrigation and overuse have seriously reduced groundwater supplies, and water pollution threatens biodiversity as well as human sources. Waterborne diseases and lack of water for sanitation cause up to 80% of human illness. Growing populations, of course, will worsen this water crisis.

- **Habitat destruction** due to agriculture, urban sprawl, and mining is the number one cause of extinction today, precipitating a biodiversity crisis. The World Resources Institute estimates that agriculture has displaced 1/3 of all temperate and tropical forests and ¼ of all grasslands; in the U.S., less than 2% of native prairie ecosystems remain. Stephen Hawking calculates that continuation of the last 200 years' rate of population growth would have us all standing shoulder-to-shoulder, literally.

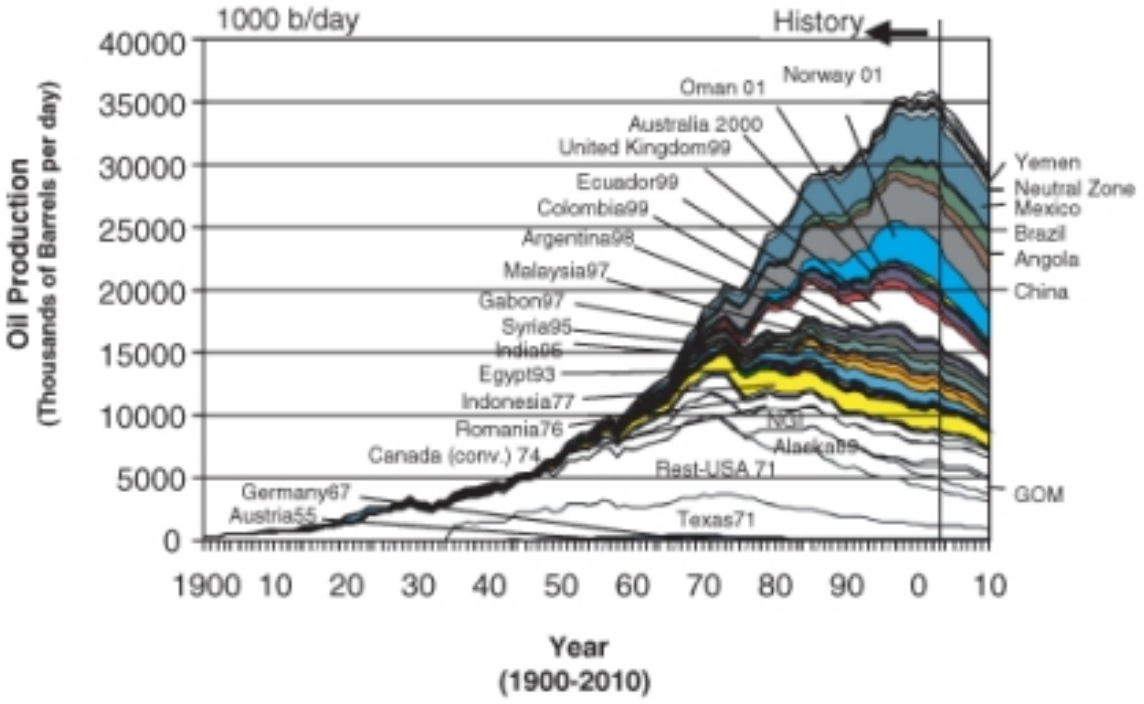

Figure 17.38: Oil production outside OPEC and former Soviet Union countries has already peaked, according to oil industry data bases for 2003 and 2004.

- Burning fossil fuels has brought about **atmospheric change**.

Sulfur and nitrogen emissions cause acid rain, which destroys fish, lakes, forests, and limestone structures. CO_2 emissions lead to global warming. Earth's surface air temperatures have risen 0.74°C (1.33°F) during the last 100 years, and will continue to rise by 1.1 to 6.4 °C (2.0 to 11.5 °F) by 2100, according to the Intergovernmental Panel on Climate Change (IPCC).

Food, oil, water, land, and air crises support the idea that our human population has already grown beyond carrying capacity with respect to environmental degradation. As world population continues to grow, what can we do to avert famine, disease, or war? How can we prevent a crash? What should be our goal?

Fortunately, individuals, organizations, and governments are beginning to address these problems. The concept of **sustainability** as a goal for human activities may hold promise for economic, social, and environmental decision-making. Although the term is recent, the concept is clearly expressed in the Great Law of the Iroquois Confederacy:

"In our every deliberation we must consider the impact of our decisions on the next seven generations." http://en.wikiquote.org/wiki/Native_American_proverbs

A sustainable activity or state can be maintained indefinitely, without compromising resources for the future. Sustainability of products and services considers complete life cycles – raw materials, manufacturing, transportation/distribution, use and re-use, maintenance, recycling and ultimate disposal. All phases must address conservation of natural and human resources and also biodiversity. Many people believe current population and lifestyles are not sustainable. Unequal distribution of resources suggests that developing countries may accelerate pressure on resources in order to improve their own lifestyles.

A preliminary tool for estimating sustainability is an **ecological footprint** analysis. Your ecological footprint is the amount of land area you would need to sustain your current lifestyle. Footprint analysis considers the resources you consume and the pollution you generate, and then calculates the amount of land which would be needed to produce equivalent *renewable* resources and process associated with waste. Air, land, water, food, and energy resources are all incorporated into the model. You can estimate your own footprint online (see Links at the end of the lesson) and compare it to that of countries throughout the world (**Figure** 17.39). Note that the average U.S. footprint is 12 times that of India, 24 times that of Somalia, and 4.4 times the world average. The last figure is worth expressing in another way: to provide everyone alive today with our western lifestyle, we'd need 4 or 5 backup planets.

To date, there is no overall agreement on a carrying capacity of Earth for humans, but many people are concerned about population growth, resource depletion and environmental degradation. Joel E. Cohen, in his book *How many people can the earth support*? summarizes three potential responses to the "population problem" identified at the beginning of the chapter. All three can contribute to the ultimate solution.

Country	Ecological footprint (global hectares per person)
Worldwide	2.2
Africa	1.1
Australia	6.6
Canada	7.6
China	1.6
European Union	4.8
Findhorn, Scotland, Ecovillage	2.56
Haiti	0.6
India	0.8
Japan	4.4
United States	9.6
Somalia	0.4

Figure 17.39: Ecological footprints measure the amount of land area required to sustain (produce replacement resources and assimilate waste) particular lifestyles. Note the 24-fold difference between citizens of Somalia and those of the US. One U.S. acre is equal to 0.405 hectares.

1. *"Make a bigger pie."* Use technology and innovation to create, conserve, and distribute resources.
2. *"Put fewer forks on the table."* Through birth control and cultural change, reduce both population size and lifestyle expectations.
3. *"Teach better manners."* Transform political and social structures toward the goal of social justice.

The human population, like all populations, has the capacity to reproduce exponentially and yet must live within a finite world. Unique among animals, however, we can utilize technology, cultural planning, and values in decisions which influence our future welfare. Which tools would you choose? What decisions will you help to make?

Lesson Summary

- According to Neo-Malthusians, the worldwide human population may have already passed Earth's carrying capacity in terms of environmental degradation, resource depletion, and unbalanced distribution of food, wealth, and development. More people will increase the danger of famine or war.
- According to the cornucopians, technology and innovation can solve any problems which arise due to human population growth. The more people, the better.

- The demographic transition model suggests that human populations pass through four stages of population growth:

Stage 1: Growth is slow and uneven, because high death rate offsets high birth rate.
Stage 2: Development and sanitation reduce death rates, so populations grow exponentially.
Stage 3: With industrialization, urbanization and contraception, births fall, and growth begins to decline.
Stage 4: Eventually, birth rate equals death rate, growth rate is zero, and the population stabilizes.

- Because this model uses late 18^{th} and 19^{th} century European data, it correlates closely with demographic transitions throughout developed nations into the 20^{th} century, but may not fit undeveloped countries.

- No country remains in Stage 1.
- A number of poor, undeveloped countries remain in stage 2; age pyramids show large youth populations.
- Many countries have entered Stage 3, with some lowering fertility rates by as much as 40%, but pyramid "youth bulges" mean they continue to grow.

- Replacement fertility varies from country to country because death rates vary.
- A few countries have reduced fertility rates below replacement and are shrinking in population.
- Shrinking countries may for a time experience economic difficulties related to an aging population.

- In September 2007, world population stood at about 6.7 billion, growing by 211,090 people each day.
- The last billion-person increase took only 12 years.
- Despite recent declines in birthrate in some developed countries, the human population will continue to increase at least until a peak in 2050 of 9.4 billion people or more.
- Many scientists believe that we humans have already overshot the carrying capacity of Earth if resource exploitation and habitat alteration are considered.
- Five factors which many believe already limit sustainable human population size are:

1. Agricultural dependence on nonrenewable fossil fuels for fertilizers, pesticides, and irrigation.
2. Dependence of industry and transportation on a finite fossil fuel supply, which has already peaked.
3. Decline in freshwater resources due to pollution and overuse.
4. Habitat destruction due to urban sprawl and agriculture, and a consequent biodiversity crisis.
5. Atmospheric changes such as acid rain and global warming – both consequences of increased fossil fuel burning.

- The concept of sustainability may hold promise for economic, social, and environmental decisions.
- Sustainability of products and services considers complete life cycles from raw materials to disposal.
- A tool for estimating sustainability is the ecological footprint.

1. The average U.S. footprint is 12 times India's, 24 times Somalia's, and 4.4 times the world average.
2. Were all people to adopt a U.S. lifestyle, we would need 4 or 5 planets to supply resources and dispose of waste sustainably.

- Potential solutions to the problems of population growth are summarized by Joel E. Cohen:

1. Create new and conserve existing resources – the technological "fix."
2. Lower population size and lifestyle expectations – cultural change.
3. Distribute resources equitably – social justice.

Review Questions

1. Describe the *overall* pattern of human population growth, beginning with our origins 200,000 years ago and compare it to the exponential and logistic models.
2. Compare the factors that influenced human population growth up to the first 1 billion mark to those which controlled growth of the last billion.
3. Summarize the 5 stages of the demographic transition model in terms of *b, d,* and *r.*
4. Explain the problems with the original, four-stage demographic transition model of human population growth. Give examples of each.
5. Explain why replacement fertility must exceed 2 children per female.
6. Use the "pop clock" links at the end of the chapter to look up the current US and world populations. Compare these to predictions for 2050 made by the UN and U.S. Census Bureau. Why do many people consider these numbers to be above Earth's carrying capacity?
7. Summarize 5 environmental effects of human activity which may act as limiting factors for population growth. How many of these relate to our use of fossil fuels, and why is this a problem?
8. Explain how ecological footprints measure sustainability, and compare them for developed and undeveloped nations.
9. Explain what Joel E. Cohen meant by suggesting that "a bigger pie," "fewer forks," and "manners" are needed to address the problems of overpopulation.
10. Consider what you know about resource limitations, population distribution, levels of consumption, technology, poverty, economics, political realities, religious views, and different human perspectives on the earth. Choose and describe 3 changes you believe would be most successful in solving the problems of worldwide population growth – and 3 changes you believe would be least successful. Support each change with reasons why you think it would be more or less effective.

Further Reading / Supplemental Links

- Joel E. Cohen, *How Many People Can the Earth Support?* Norton, 532 pp, 1995.
- http://www.bradshawfoundation.com/journey
- http://desip.igc.org/mapanim.html
- http://www.eoearth.org/article/Human_population_explosion
- http://www.globalchange.umich.edu/globalchange2/current/lectures/human_pop/human_pop.html
- http://www.census.gov/main/www/popclock.html
- http://www.bestfootforward.com/
- http://www.footprintnetwork.org/gfn_sub.php?content=footprint_overview
- http://www.panda.org/news_facts/publications/living_planet_report/index.cfm
- http://www.worldchanging.com/archives/006904.html

- http://lca.jrc.ec.europa.eu/lcainfohub/introduction.vm
- http://www.ilea.org/leaf/richard2002.html

Vocabulary

carrying capacity The maximum population size that a particular environment can support without habitat degradation.

cornucopian A person who believes that people and markets will find solutions to any problems presented by overpopulation.

demographic transition theory Theory that proposes that human populations pass through 4 or 5 predictable stages of population growth.

density-dependent factor Factor which has the potential to control population size because its effects are proportional to population density.

density-independent factor Factor which may affect population size or density but cannot control it.

ecological footprint The amount of land area needed to sustain a particular lifestyle, matching its resource consumption and pollution to necessary renewable resource production and waste assimilation.

exponential model (geometric or J-curve) A model of population growth which assumes that growth rate increases as population size increases.

k-selected species Species which have adaptations which maximize efficient utilization of resources, conferring competitive strength near or at carrying capacity.

logistic (S-curve) A model of population growth which assumes that the rate of growth is proportional to both population size and availability of resources.

Neo-Malthusians Individuals who believe that human population growth cannot continue without dire consequences.

population A group of organisms of a single species living within a certain area.

r-selected species Species which have adaptations which maximize growth rate, r.

replacement fertility The number of births per female required to maintain current population levels; includes 2 children to replace the parents and a fraction of a child extra to make up for early mortality and sex ratio differences at birth.

Points to Consider

- Now that you have studied some of the data on human population growth, return to the questions in the introduction to this lesson and consider whether or not your answers have changed.

1. Are we built for growth – or for efficient use of resources?
2. Does our growth pattern resemble a J, or an S? Why?
3. Do you think Earth has a carrying capacity for humans?
4. Do you think we are we in danger of extinction?
5. What exactly is our "population problem," and what do you think we should do to solve it?

- Jared Diamond, reflecting on the fates of past societies facing problems of sustainability, in Collapse: How Societies Choose to Fail or Succeed (2005), p. 522, says: "Two types of choices seem to me to have been crucial in tipping … outcomes towards success or failure: long-term planning, and willingness to reconsider core values. On reflection, we can also recognize the crucial role of these same two choices for the outcomes of our individual lives." Do you think the worldwide human population will be able to make these choices wisely?

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Chapter 18

Ecology and Human Actions

18.1 Lesson 18.1: The Biodiversity Crisis

Lesson Objectives

- Compare humans to other species in terms of resource needs and use, and ecosystem service benefits and effects.
- Define the concept of biodiversity.
- Quantify Earth's species diversity, according to scientists' current understanding.
- Describe patterns of biodiversity in space.
- Trace changes in biodiversity throughout Earth's history.
- Examine the evidence for the Sixth Extinction.
- Compare the Sixth Extinction to major extinctions before humans.
- Discuss the direct economic benefits of biodiversity.
- Evaluate ecosystem services provided by biodiversity.
- List the intangible (cultural, spiritual, religious) benefits of biodiversity.
- Relate biodiversity to social and political stability.
- Consider that biodiversity has intrinsic value apart from benefits to humans.
- Assess the potential for early human activities to contribute to Ice Age extinctions of large animals.
- Identify habitat loss as the primary cause of the Sixth Extinction.
- Relate the introduction of exotic species to loss of biodiversity.
- Explain the extent to which over exploitation has affected all levels of biodiversity.
- Connect energy use to extinction.
- Describe the effects of population growth and unequal distribution of resources on biodiversity.
- Recognize that pollution of water, land, and air contributes to the loss of species.
- Acknowledge that your daily activities and decisions can significantly help to protect

biodiversity.
- Evaluate your consumption – of food, clothing, furniture, and cleaning products.
- Appreciate the importance of water resources and know how to use them wisely.
- Evaluate your choice and use of energy sources.
- Assess the importance of minimizing waste, and of using best practices for waste disposal.
- Know how to avoid transporting and releasing exotic species.
- Realize that you can practice sustainable management of your own land, from small yards to local, state, and federal lands which also belong to you.
- Describe sustainability and its role in decision-making.
- Explain how learning and active citizenship can contribute to protecting biodiversity.

Introduction

Humans, like all species, depend on certain natural resources for survival. We depend on land and soils to grow crops, which transform solar energy into food. We use the Earth's freshwater lakes, rivers, and groundwater for drinking. We rely on the atmosphere to provide us with oxygen and to shield us from radiation. We rely on Earth's biodiversity for food, clothing, and medicines. We utilize all of the "basic four" (biodiversity, land, water, air) for recycling of nutrients and disposal of waste. Natural ecosystems, as Odum suggests, provide services for all species: they maintain soil, renew the atmosphere, replenish freshwater supplies, dispose of wastes, and recycle nutrients. In our dependence on these services, we are like all other species.

Yet in many ways, we do not behave like other species. We supplement food and animal energy with fossil fuel energy. We harvest natural resources to exhaustion, and produce waste beyond levels that the Earth can process. We alter biodiversity, land, water, air and fossil fuels beyond nature's ability to repair. As you learned in your study of population biology, our population has grown beyond Earth's carrying capacity, compounding problems of resource use and waste disposal. Only recently have we learned to appreciate the full value of these resources – and the potential for harm from our own activities. Our economics have not caught up to our relatively new understanding: we do not yet pay the costs of maintaining all of "nature's services."

This lesson will explore biodiversity – the "millions of organisms and hundreds of processes - operating to maintain a livable environment." The topic is timely, critical, and colorful: you will encounter warnings of a Biodiversity Crisis and the Sixth Extinction, and species identified as "an Elvis taxon" or "a Lazarus taxon." More importantly, by the end of your study, you will have some tools you can use in your daily life to help protect the great diversity of Earth's life.

What is Biodiversity?

"The first rule of intelligent tinkering is to save all the pieces." –attributed to Aldo Leopold, but probably a shortened version of: ***"To save every cog and wheel is the first precaution of intelligent tinkering."* - Aldo Leopold, *Round River: from the Journals of Aldo Leopold*, 1953**

What are the "cogs" and "wheels" of life?

Although the concept of **biodiversity** did not become a vital component of biology and political science until nearly 40 years after Aldo Leopold's death in 1948, Leopold – often considered the father of modern ecology - would have likely found the term an appropriate description of his "cogs and wheels." Literally, biodiversity is the many different kinds (*diversity*) of life (*bio-*). Biologists, however, always alert to levels of organization, have identified three measures of life's variation. **Species diversity** best fits the literal translation: the number of different species (see the chapter on Evolution of Populations) in a particular ecosystem or on Earth (**Figure** 18.1). A second measure recognizes variation *within* a species: differences among individuals or populations make up **genetic diversity**. Finally, as Leopold clearly understood, the "cogs and wheels" include not only life but also the land (and sea and air) which supports life. **Ecosystem diversity** describes the many types of functional units formed by living communities interacting with their environments.

Although all three levels of diversity are important, the term biodiversity usually refers to species diversity. How many species do you think exist on Earth? What groups of species do you think are most abundant? Consider your own experience, and your study of biology up to this point. Think carefully, and write down your answer or exchange ideas with a classmate before you read further.

What is the Species Diversity of Earth?

There are three good answers to this question. As a member of one of Earth's most intriguing species, you should know them all!

1) Scientists have identified about 1.8 million species. (**Figure** 18.2)

The relative numbers of species in each of the six kingdoms of life is shown in **Figure A** 18.2. The Animal Kingdom (dominated by the Insects, as shown in **Figure B** 18.2) includes the great majority of known species, and Archaebacteria, by far the fewest. Most scientists agree that Eubacteria and Archaebacteria are seriously underrepresented, due to their small size and chemistry-based diversity. This leads to a second, and perhaps better answer to our question:

2) No One Knows How Many Species Currently Live on Earth!

Does this lack of knowledge surprise you? Scientists are still discovering new species - not only microorganisms but also plants, animals, and fungi. At least 5 new species of marsupials,

Figure 18.1: The most accessible definition of biodiversity is species diversity. How many species exist on Earth?

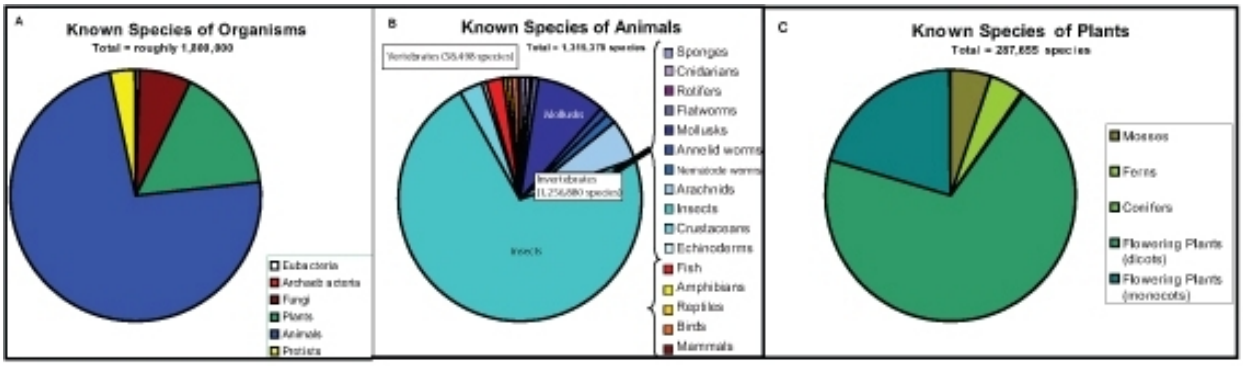

Figure 18.2: Among 1.8 million identified species (A), 1,315,378 are Animals (B), 287,655 are Plants (C), and only 259 are Archaebacteria. The Animal Kingdom is dominated by the Class Insecta, and the Plant Kingdom is dominated by flowering plants.

25 primates, 3 rabbits, 22 rodents, 30 bats, 4 whales or dolphins, a leopard, and a sloth were identified between 2000 and 2007 – and these include only mammals! The vast majority of Eubacteria, Archaebacteria, Protist, and even Insect species may be yet unknown because their small size, remote habitats, and the chemical distinctions between species make them so difficult to detect. These challenges, however, have not prevented scientists from estimating Earth's biodiversity – bringing us to the third answer to our question:

3) Scientists Estimate that Between 5 and 30 Million Species Inhabit the Earth.

Estimates vary widely – from 2 million to 117.7 million, underlining our lack of knowledge. Most estimates fall between 5 and 30 million. Much remains to be learned about the diversity of microorganisms. For example, scientists have recently discovered that Archaebacteria – originally considered limited to extreme environments - may constitute as much as 40% of the ocean's microbial biomass. Few species have been identified. Estimates of global diversity of the better-studied Eubacteria vary from millions to billions, with orders of magnitude of error. As for multicellular organisms, the most "species-dense" terrestrial ecosystems, such as coral reefs and tropical rain forests, harbor most of the undiscovered species (**Figure** 18.3). Ironically, these ecosystems are also disappearing quickly. In summary, our estimates of biodiversity remain crude. However, the following conclusion is clear: given the current rapid loss of species, we will never know many of the species we are losing.

Figure 18.3: Coral reefs (above) and tropical rain forests (below) have the greatest biodiversity of the many ecosystems on earth. They are also among the most threatened habitats. Because our knowledge of their species is incomplete, we are clearly losing species we do not (and never will) know.

Biodiversity Patterns in Space

Are Earth's 1.8 million known species evenly distributed across its surface? You may already be aware that the answer is a resounding "No!" We will compare two regions with relatively high diversity to begin our analysis.

Minnesota has relatively high ecosystem diversity, because three of the Earth's six major terrestrial biomes converge in this state (Prairie, Deciduous Forest, and Coniferous Forest). By contrast, Costa Rica comprises almost entirely of Tropical Rain Forest, and has only one quarter of the land area of Minnesota (**Figure** 18.4).

Figure 18.4: The state of Minnesota () includes three major biomes and four times the land area of the country of Costa Rica (), which is predominately a tropical rainforest. compares the biodiversity of Minnesota to that of Costa Rica.

You might expect, then, that Minnesota would have a higher species diversity. Several groups of organisms are compared in the **Figure** 18.5. Note that a column is included for you to research your own state or region!

Clearly, biodiversity is much higher in Costa Rica than in Minnesota. Collecting leaves for your biology class in Costa Rica, you would need to study 2,500 different trees in order to identify the species! And you'd need to look carefully to distinguish tree leaves from those of the many **epiphytes** (plants which grow on top of others), vines, and strangler figs which climb the trunks and branches, "cheating" their way to the sunlight at the top of the canopy. In Minnesota, keys to native trees include just 42 species of conifers and deciduous broadleaved species. There, vines are relatively rare, and epiphytes are limited to colorful lichens.

The differences in biodiversity between Minnesota and Costa Rica are part of a general worldwide pattern: biodiversity is richest at the equators, but decreases toward the poles. Temperature is undoubtedly a major factor, with warmer, equatorial regions allowing year-round growth in contrast to seasonal limitations nearer the poles.

Generally, the more species, the more niches – so diversity begets diversity.

Group of Organisms	Number of Species: Minnesota	Number of Species: Costa Rica	Number of Species: Your State
Amphibians	18	150 	
Reptiles	27 	210	
Birds	400 (but 96 of these migrate, spending winter in the Rainforest)	848 	
Hummingbirds	1 	852	
Mamma ls	80	200 	
Bats	7 	100	
Butterflies	140	1000 	
Orchids	42 	1200	
Trees	43	2500 	

Figure 18.5: A comparison of species diversity within categories supports the increase in diversity from the poles to the equators. Costa Rica's increased diversity is due in part to greatly increased niches: diversity begets diversity! For example, poison dart frogs mature in tiny epiphyte pools, and strangler figs climb existing trees and "starve" their hosts of sunlight. Does your state or region support this overall spatial pattern of biodiversity?

Does your country, state or region fit the general pattern of decreasing biodiversity from equator to poles?

Biodiversity Patterns in Time

How has Earth's biodiversity changed across time? The fossil record is our window into this pattern, although the window has limitations. Microorganisms are poorly preserved and distinguished only with difficulty; gene sequence studies of living bacteria have begun to fill in some missing data. For all organisms, recent rock layers are more accessible and better preserved than ancient ones.

Despite these drawbacks, fossils and gene studies show a distinct pattern of increasing biodiversity through time. As discussed in the chapter on the *History of Life,* the origin of life is not clearly understood; evidence suggests that life did not appear on Earth until perhaps 4 billion years ago. For several billion years, unicellular organisms were the only form of life. During that time, biodiversity clearly increased, as Eubacteria and Archaebacteria emerged from a common ancestor some 3 billion years ago, and Eukaryotes emerged by endosymbiosis about 2 billion years ago. However, we have not accurately measured the diversity of even today's microorganisms, so we have little understanding of changes in the diversity of microorganisms beyond these major events.

The emergence of multicellular life about 1 billion years ago certainly increased biodiversity, although we have little way of knowing whether it might have negatively affected the diversity of microorganisms. Fossils remain relatively rare until the famed Cambrian explosion 542 million years ago. Since then, a much more detailed fossil record (**Figure** 18.6) shows a pattern of increasing biodiversity marked by major extinctions.

The dramatic increase indicated for the last 200 million years is somewhat disputed. Some scientists believe it is a real increase in diversity due to expanding numbers of niches – diversity begets diversity, again. Others believe it is a product of sampling bias, due to better preservation of more recent fossils and rock layers. Most scientists accept the general pattern of increasing diversity through time, interpreting the magnificent biodiversity of life on Earth today as the result of billions of years of evolution.

Most scientists also accept at least the five major mass extinctions shown in **Figure** 18.6, and some hold that regular cycles govern extinction. Causes for these extinctions (more completely discussed in the *History of Life* chapter) remain incompletely understood; hypotheses include global climate change, major volcanic and continental drift events, dramatic oceanic change, and/or extraterrestrial impact or supernova events.

Increasingly accepted is a current Sixth or Holocene Extinction event. According to a 1998 survey by the American Museum of Natural History, more than 70% of biologists consider the present era to be a sixth mass extinction event - perhaps one of the fastest ever. We will explore the Sixth, or Holocene, Extinction in the next section of this lesson.

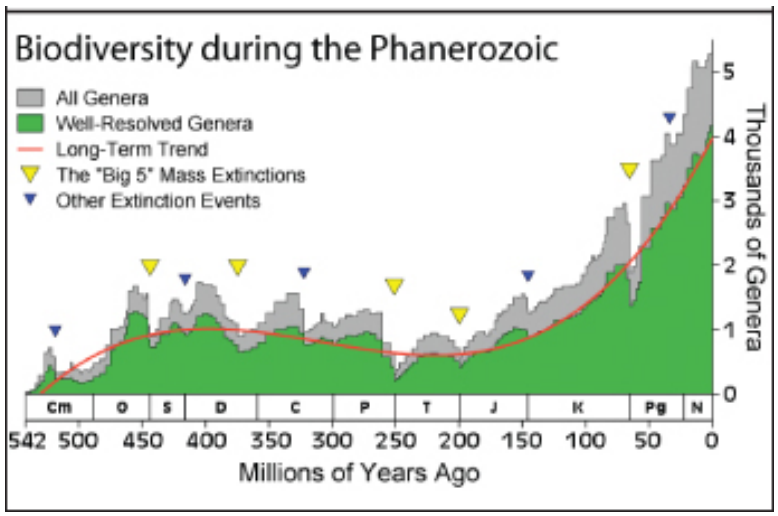

Figure 18.6: The fossil record for marine species over the past 542 million years shows a gradual increase in biodiversity interrupted by five major extinctions. Some scientists view the recent rapid rise in diversity as a result of better preservation of more recent rock layers and fossils.

The Current Loss of Biodiversity

"For one species to mourn the death of another is a new thing under the sun." **-Aldo Leopold** *A Sand County Almanac,* 1949

Over 99% of all species that have ever lived on Earth are extinct. During the 5 major extinctions recorded in the Phanerozoic fossil record (**Figure** 18.6), more than 50% of animals disappeared. Evidently, extinction is natural. However, current extinctions may differ significantly in rate and cause. The IUCN (International Union of Concerned Scientists) has documented 758 extinctions since 1500 CE; for example, 6 species of giant, flightless *Moa* (**Figure A** 18.7) disappeared from New Zealand shortly after the arrival of Polynesians. Estimates of extinctions for the last century range from 20,000 to 2,000,000 species; as for diversity, we simply do not know the true figure.

Many scientists begin the Sixth Extinction with the Ice Age loss of large mammals and birds - part of a continuum of extinctions between 13,000 years ago and now. During that time, 33 of 45 genera of large mammals became extinct in North America, 46 of 58 in South America, and 15 of 16 in Australia. Climate change and/or human "overkill" are hypothetical causes. Supporting the significance of the "sudden" arrival of humans are the low numbers in Europe and South Africa, where humans had coevolved with large animals. The woolly mammoth (**Figure B** 18.7) is one of the many examples of large mammal extinctions from this period.

The first species to become extinct during recorded human history was the Dodo (**Figure C** 18.7), a flightless bird which had evolved without predators on an island in the Indian

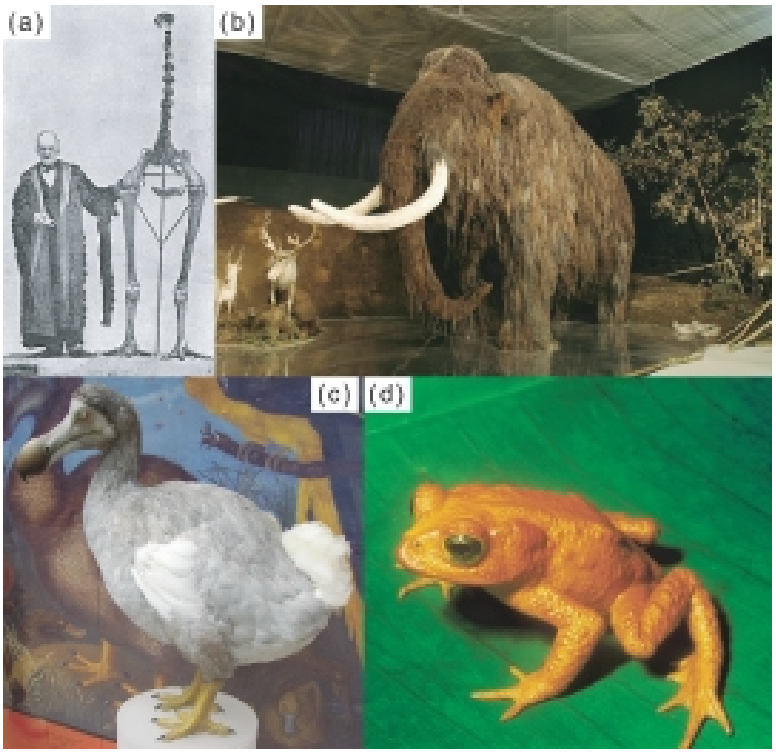

Figure 18.7: A gallery of species which have succumbed to the Sixth Extinction: A: one of six species of birds which disappeared after Polynesians first arrived and began to hunt and clear forests in New Zealand about 1500 CE. B: reconstruction of a woolly mammoth, one of many large mammals which became extinct at the end of the last Ice Age, due to human hunting, disease, and/or climate change. C: a reconstruction of the meter-tall flightless Dodo, which disappeared within a hundred years of its discovery, probably due to forest destruction and introduced predators. D: the Golden Toad recently discovered in 1966, has been officially extinct since 1989. Amphibians as a group have declined sharply throughout the world during the past three decades.

Ocean. Described in 1581, the fearless Dodo experienced hunting, forest habitat destruction, and introduced predators, and became extinct before 1700 – a story repeated for many more species over the following three centuries. Unfortunately, the story extends back in time, as well; over the past 1100 years, human activity has led to the extinction of as many as 20% of all bird species… a tragic loss of biodiversity.

Harvard Biologist E.O. Wilson estimated in 1993 that the planet was losing 30,000 species per year - around three species per hour. In 2002, he predicted that if current rates continue, 50% of today's plant and animal species will be extinct within the current century – compared to hundreds of thousands or even millions of years for pre-human mass extinctions. A dramatic global decline in amphibian populations in less than 30 years headlines the recent rise in extinction. Herpetologists report that as many as 170 species have become extinct within that time, and at least one-third of remaining species are threatened. Costa Rica's Golden Toad (**Figure D** 18.7), first described in 1966, was last seen in 1989 and has become a poster species for amphibian declines.

Why is Biodiversity Important? What are We Losing?

Why should humans care if biodiversity declines? Does it matter that we have 170 fewer amphibians, or that we are losing thousands of species each year, when the Earth holds millions of other species, and life has been through extinction before? The answer is a definitive yes! It matters to us even if we consider only the economic and spiritual benefits to humans. It matters to us because we do not even understand the myraid of indirect benefits – now recognized as **ecosystem services**- that we reap from other species. And, of course, it matters to other species as well.

Direct Economic Benefits of Biodiversity

- ***Food Supply***: **Monocultures** (large-scale cultivation of single varieties of single species) are extremely vulnerable to disease. A water mold caused the infamous Irish potato famine where potatoes had been bred from a single Incan variety. As recently as 1970, blight swept the corn belt where 80% of maize grown in the U.S. was a single type. According to the Food and Agricultural Organization of the United Nations, humans currently cultivate only 150 plant species, and just four provide over half of the food we eat. Just 15 animal species make up over 90% of our livestock.

Potential for hybridization requires a diverse "bank" of wild, native species. Contemporary breeders increase genetic diversity by hybridizing crop species with wild species adapted to local climate and disease (**Figure** 18.8).

- ***Clothing, Shelter, and Other Products***: As many as 40,000 species of plants, animals, and fungi provide us with many varied types of clothing, shelter and other

Figure 18.8: Wild varieties of domesticated crops, such as this unusually shaped Latin American maize, hold the potential to enhance productivity, nutritional value, adaptation to local climates, and resistance to local diseases through hybridization. Loss of biodiversity limits our ability to increase the genetic diversity of crops.

products. These include timber, skins and furs, fibers, fragrances, papers, silks, dyes, poisons, adhesives, rubber, resins, rubber, and more.

- ***Energy***: In addition to these raw materials for industry, we use animals for energy and transportation, and biomass for heat and other fuels. Moreover, hydroelectric power depends on ecosystem structure: Chinese scientists calculated that the economic benefits of maintaining forest vegetation in the Yangtze River watershed "produced" more than twice the economic value of timber (had it been harvested) in annual power output.

- ***Medicine and Medical Models***: Since the first microorganisms competed for food, evolution has been producing chemicals for "warfare" and "defense" in bacteria, fungi, plants, and animals; **Figure** 18.9 shows several used by humans. According the American Museum of Natural History Center for Biodiversity Conservation (AMNH-CBC), 57% of the most important prescription drugs come from nature, yet only a fraction of species with medicinal potential have been studied.

Unique features of certain species have opened windows into how life works. For example, the Atlantic squid's giant axon revealed the basics of neurophysiology, and the horseshoe crab's (**Figure D** 18.11) optic nerve and photoreceptors taught us how vision works. Other animals serve as disease models; as far as we know, other than humans, only armadillos suffer from leprosy, and only sea squirts form kidney stones.

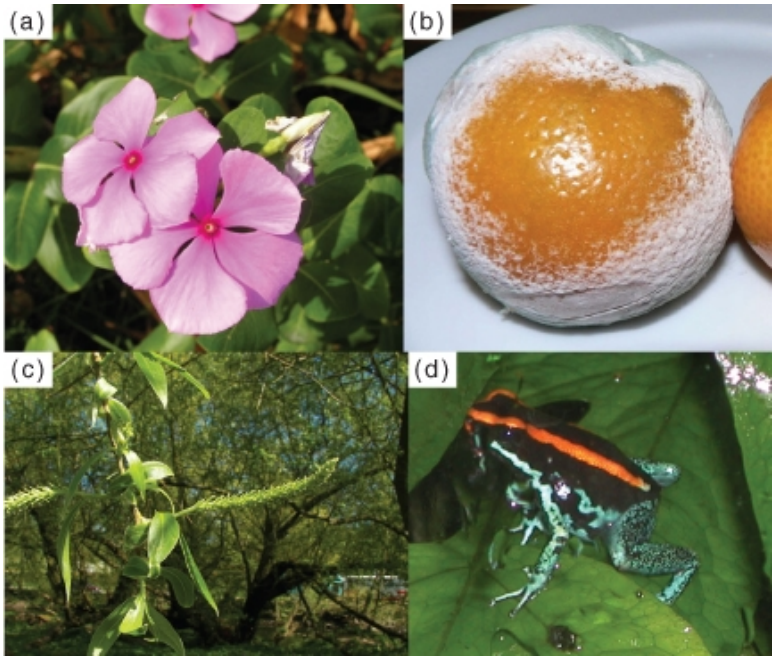

Figure 18.9: A pharmacopoeia of the living world: The Rosy Periwinkle (A) is the source of two chemotherapy drugs effective against leukemias. The mold (B) produces the antibiotic penicillin to defend its territory (in this case, a mandarin orange) from competing microorganisms. Aspirin originates in the bark of the White Willow (C). And several species of tropical frogs in the genus (D) produce poisons used by South American tribes for hunting with darts.

- ***Efficient Designs: Inspiration for Technology***: **Biomimicry**, also known as biomimetics or **bionics**, uses organisms for engineering inspiration and human innovation. Rattlesnake heat-sensing pits, for example, suggested infrared sensors. Zimbabwe's Eastgate Centre **Figure** 18.10 incorporates air-conditioning principles from termite mounds. The 2006 Mercedes-Benz *Bionic* employs the body shape of the yellow box fish to combine high internal volume and efficient aerodynamics. Biomimetics professor Julian Vincent estimates that only 10% of current technology employs the highly efficient biological designs crafted by evolution and natural selection. Loss of biodiversity can be viewed as the loss of millions of years of evolutionary wisdom.

Figure 18.10: Bionics, or biomimicry, engineers structures based on biological designs made efficient by millions of years of evolution and natural selection. Above: The air-conditioning efficiency of a termite mound (left) inspired the design of the Eastgate Centre in Zimbabwe (right), which requires just 10% of the energy needed for conventional building of the same size. Below: The rigid exoskeleton and low-drag body shape of the tropical yellow box-fish (left) inspired the 2006 Mercedes-Benz (right), which combines large internal volume with optimal aerodynamics.

- ***Warnings of Toxins and Other Ecosystem Disruptions***: If you know how miners use canaries to detect poisonous gases underground, you will understand how widespread extirpation of peregrine falcons (**Figure E** 18.11) warned us about the dangers of the pesticide DDT and food chain concentration of toxins.

Indirect Benefits of Biodiversity: Ecosystem Services

- ***Increasing Ecosystem Productivity***: Ecologist David Tilman compared grassland plots to show that increasing species diversity increased overall productivity (yield). Different plants utilize different resources, so a variety of plants may more completely use resources within an area. As noted above, diversity also reduces system vulnerability to pests and disease.

- ***Increasing Ecosystem Stability***: Tilman observed his grassland plots through several cycles of drought and documented a similar relationship between biodiversity and stability. Plots which were more diverse were more resistant to drought and later recovered more completely. Reducing ecosystem vulnerability to pests and disease may also be a factor in the relationship between diversity and stability. As you have learned before, diversity among individuals within a species increases the chance that at least some will survive environmental change; similarly, diversity among species within an ecosystem increases the chance that at least some species will survive environmental change.

- ***Maintaining the Atmosphere***: As you learned in the chapters on photosynthesis and respiration, plants and algae produce the O_2 which makes up 20% of the atmosphere essential to aerobic organisms, and remove CO_2 produced by respiration and burning fossil fuels. As Joseph Priestley expressed this service, plants "restore the air" which has been "injured by the burning of candles" or "infested with animal respiration." O_2 is also critical to life because it helps to maintain the ozone shield, protecting life from dangerous Ultra-Violet radiation.

- ***Maintaining Soils***: Soil microorganisms maintain nutrients in complex but critical chemical pathways. Vegetation and litter prevent erosion of soils which require thousands of years to form. Estimates suggest that erosion destroys as many as 3 million hectares of cropland annually, and that as much as one-fifth of the world's cropland is "desertified" through salination, acidification, or compacting.

- ***Maintaining Water Quality***: Water treatment plants rely in large part on microorganisms for water purification, and natural systems do the same. In nature, wetland, waterway, and watershed root systems combine with soil adsorption and filtration to accomplish water purification. When New York City decided to restore the Catskill watershed, their $1-1.5 billion investment in "natural capital" contrasted favorably with the $6-8 billion initial cost and $300 million annual operating cost of a new treatment plant.

- ***"Fixing" Nitrogen***: One of the most amazing aspects of biological systems on earth is their absolute need for nitrogen – to build the proteins and nucleic acids upon

which life depends – and their nearly universal dependence on microorganisms to "fix" atmospheric N_2 gas and recycle the nitrogen of waste and death. Only after the bacterial "service" of processing nitrogen is it available in usable chemical form to plants, and through them, to animals (**Figure A** 18.11).

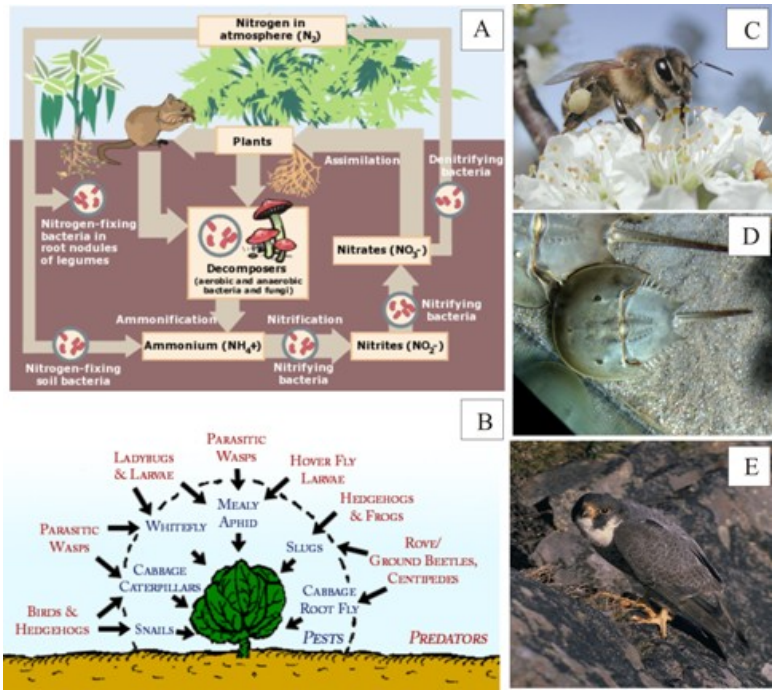

Figure 18.11: Ecosystem services which depend on biodiversity include nitrogen fixation (A), pest control (B), pollination (C), medical models such as the horseshoe crab optic nerve and photoreceptors (D), and early warning about toxins, e.g. the peregrine falcon's extirpation by the pesticide DDT (E).

- ***Nutrient Recycling and Waste Disposal***: Bacteria and nitrogen are not the only contributors to the waste management services of ecosystems. Fungi, protists, and scavengers help to decompose waste and dead organisms so that new life can reuse the available nutrients.

- ***Pollination***: The list of biotic pollinators, essential for sexual reproduction in many plants, is long including not only insects such as wasps, bees, ants, beetles, moths, butterflies, and flies, but also fruit bats and birds such as hummingbirds, sunbirds, spiderhunters, and honeyeaters. Although U.S. crops have relied on commercial honeybees (which are "migrated" to keep pace with maturing crops!), native pollinators in nearby forests or wild grasslands have been shown to improve the productivity of apples or almonds by 20%. The American Institute of Biological Sciences estimates that

native insect pollination is worth $3.1 billion annually. Current alarm over honeybee colony collapse highlights the importance of biodiversity to the ecosystem service of pollination.

- ***Pest and Disease Control***: According to the AMNH-CBC, farmers spend $25 billion annually on pesticides, while predators in natural ecosystems (**Figure B** 18.11) contribute 5 to 10 times that value in pest control. Costs associated with the use of chemical pesticides (such as water pollution) add to the value of natural pest control. Natural enemies are adapted to local environments and local pests, and do not threaten each other's survival (or ours!) as do broad-spectrum chemical pesticides. Preservation of natural enemies is associated with preservation of plant diversity, as well. Disrupted ecosystems can lead to increasing problems with disease. In Africa, deforestation has led to erosion and flooding, with consequent increases in mosquitoes and malaria.

Aesthetic Benefits of Biodiversity

- ***Cultural, Intellectual, and Spiritual Inspiration***: Music, art, poetry, dance, mythology, and cuisine all reflect and depend on the living species with whom we share the Earth. Our cultures reflect local and regional variations, and as such, biodiversity underlies our very identities. The beauty and tranquility of living ecosystems have inspired environmentalists (Rachel Carson, Aldo Leopold), spiritualists (Thomas Berry), and writers such as (Barry Lopez) throughout history. Recently, the increasing distance of human society from the natural world has raised concerns about our psychological and emotional health; E.O. Wilson has proposed that *biophilia* (love of the living world) is an increasingly ignored part of our human psyche, and Richard Louv believes that too many of our children suffer from "nature deficit disorder" caused by our increasing alienation from nature.

- ***Recreational Experiences***: Many people choose to use vacation and recreation time to explore natural ecosystems. Outdoor recreational activities – many of which are increasing in popularity - include hunting, fishing, hiking, camping, bird-, butterfly- and whale- watching, gardening, diving, and photography. Indoor hobbies such as aquariums also celebrate biodiversity. For Costa Rica, Ecuador, Nepal, Kenya, Madagascar, and Antarctica, ecotourism makes up a significant percentage of the gross national product. Ideally, ecotourism involves minimal environmental impact, conservation of bio- and cultural diversity, and employment of indigenous peoples.

Political and Social Benefits of Biodiversity

Some analysts relate biodiversity to political and social stability. Unequal access to food, clothing, water, and shelter provided by diverse ecosystems threatens social equity and stability. Land ownership and land use practices which threaten biodiversity often marginalize

poorer people, forcing them into more ecologically sensitive areas and occupations. Poverty, famine, displacement, and migrations are problems related to loss of biodiversity which have already led to billions of dollars in relief costs and significant local armed conflict.

Intrinsic Value of Biodiversity

Many people value biodiversity for its inherent worth, believing that the existence of such a variety of genes, species, and ecosystems is reason enough for our respect. Intrinsic value goes beyond economic, aesthetic, environmental, and political benefits. For many people, intrinsic value alone imposes great responsibility on us to monitor our actions in order to avoid destroying the diversity of life.

Why is biodiversity important? It supplies us with essential resources, raw materials, and designs which have direct economic value. It enhances the stability and productivity of ecosystems which in turn provide essential, under-appreciated services. These services, too, have great economic value, although we are only beginning to recognize their importance as we experience their loss. Biodiversity is critical for cultural identity, spiritual and intellectual inspiration, and our own re-creation. Biodiversity goes hand-in-hand with social and political stability. And for many people, biodiversity has inherent worth apart from its many benefits for us and our environment.

Biodiversity is critically important for us and for the Earth, and it is declining at an unprecedented rate. What is causing current extinctions? What can we – what can YOU – do to help?

Causes of the Sixth Extinction: Human Actions and the Environment

What are the causes of the Sixth Extinction? There is nearly universal agreement that most result from human activities (**Table** 18.1 and **Figure** 18.12). Although our activities have changed, we remain the single species most able to alter the Earth's genetic, species, and ecosystem biodiversity.

Table 18.1:

Continent/Island	Human Settlement (Years Before Present)	Extinctions Which Followed
Africa, Eurasia	Humans evolve here	relatively few extinctions
Indonesia	50,000	50% of large mammal species
Australia	40,000	55 species large mammals, reptiles, and birds

Table 18.1: (continued)

Continent/Island	Human Settlement (Years Before Present)	Extinctions Which Followed
North and South America	10,000 - 12,500	70-80% of large mammals (at least 135 species) within 1000 years
Mediterranean Islands	10,000	large mammals and reptiles
West Indies	7,000	Mammals, birds, reptiles all 5 endemic mammals of Puerto Rico
Madagascar	2,000	virtually all large endemic land mammals, reptiles, and birds within 1500 years
Hawaiian Islands	1,500 (Polynesians) 250 (Europeans)	2/3 of native vertebrate species, 90% of bird species after European arrival, 20 more bird species
New Zealand	1,300	No mammals originally Frogs, lizards, and over 1/3 (40 species) of birds

Convincing evidence for human responsibility for Ice Age extinctions is outlined in **Figure** 18.12. Comparing Ice Age to pre-human extinctions provides more evidence:

- Ice Age extinctions affected large animals disproportionately; pre-human extinctions affected all body sizes.
- Ice Age extinctions occurred at different times in different regions; pre-human extinctions were global and simultaneous.
- Recent extinctions follow human migration with regularity.
- The "syncopated" pattern does not fit climate change, and earlier interglacial periods did not see similar extinctions.

Although the data above has led to considerable agreement about human responsibility for the early Holocene extinctions, scientists still debate exactly how human activities caused extinctions. Hypotheses include:

1. **Overkill**: Animals outside Africa and Eurasia evolved in the absence of humans. Many

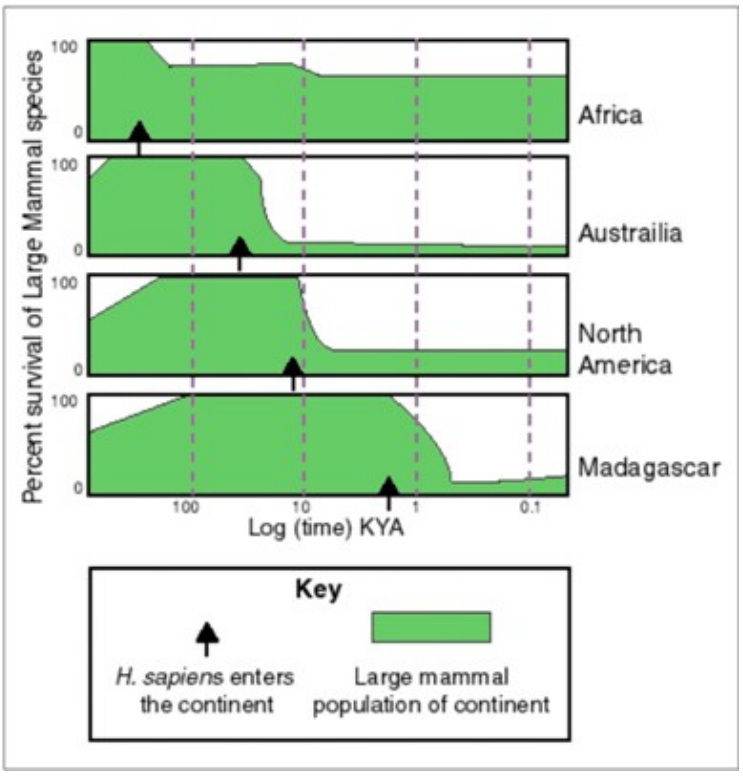

Figure 18.12: Large animal extinctions followed the arrival of humans in many regions of the world, suggesting that human activities caused the extinctions.

did not fear humans and would have been easily killed, explaining the disproportionate numbers of large species affected.
2. **Cascade effects**: Extinctions of very large animals could have had major effects on ecosystems, including secondary extinctions. Loss of predators could have led to overpopulation and starvation of prey species. Loss of large herbivores would have affected their predators. Removal of even a single **keystone species** could have destabilized complex ecosystem interactions, leading to multiple extinctions.
3. **Disease**: Humans often brought along rats, birds, and other animals as they migrated to new regions. Animals in those new regions, however, would not have evolved resistance to the diseases they carried. Avian malaria, for example, is still spreading through Hawaii, having already caused the extinctions of many bird species.
4. **Predation by exotic animals**: The rats, birds, and other animals accompanying humans brought not only disease but also new appetites to regions where animals had evolved without predators. Like humans, these animals found the "naïve" prey easy to capture.
5. **Habitat destruction**: Deforestation and agriculture accompanied humans, and the loss of habitat inevitably resulted in loss of species.

These effects of early human habitation foreshadow today's even greater threats to biodiversity. Overpopulation, industrialization, technology, cultural differences, and socioeconomic disparities compound the six major causes of today's Biodiversity Crisis. Most experts agree on the primary cause of extinction today:

Causes of Extinction #1: Habitat Loss

Habitat loss, degradation and fragmentation is universally accepted as the primary threat to biodiversity. Agriculture, forestry, mining, and urbanization have disturbed over half of Earth's vegetated land. Inevitably, species disappear and biodiversity declines.

Conversion for **agriculture** is a major reason for habitat loss. Within the past 100 years, the area of land cultivated worldwide has increased 74%; grazing land increased 113%. Agriculture has cost the United States 50% of its wetlands and 99% of its tallgrass prairies. Native prairie ecosystems (**Figure** 18.13) - which comprise of thick, fertile soils, deep-rooted grasses, a colorful diversity of flowers, burrowing prairie dogs, owls and badgers, herds of bison and pronghorns, and booming prairie chickens, - are virtually extinct.

The largest cause of deforestation today is **slash-and-burn agriculture** (**Figure** 18.14), used by over 200 million people in tropical forests throughout the world. Depletion of the surprisingly thin and nutrient-poor soil often results in abandonment within a few years, and subsequent erosion can lead to desertification. Half of Earth's mature tropical forests are gone; one-fifth of tropical rain forests disappeared between 1960 and 1990. At current rates of deforestation, all tropical forests will be gone by 2090.

Figure 18.13: Habitat loss is the #1 cause of extinction today. In the U.S., over 99% of tallgrass prairies have been eliminated in favor of agriculture. Big bluestem grasses as tall as a human (center) and (clockwise from top) prairie chickens, prairie dogs, burrowing owls, yellow and purple coneflowers, blue grama grass, and bison make up part of the prairie community.

Figure 18.14: Slash-and-burn agriculture is practiced by over 200 million people throughout the world; this photo was taken in Panama. Because of thin, nutrient-poor soils, plots are abandoned within just a few years. Experts predict that if current rates continue, all tropical forests will be gone by 2090.

Poverty, inequitable land distribution, and overpopulation combine in third world countries to add pressure to already stressed habitats. Use of firewood, charcoal, crop waste, and manure for cooking and other energy needs further degrade environments, threatening biodiversity through habitat loss.

Causes of Extinction #2: Exotic (Alien or Invasive) Species

Technology has made the human species the most mobile species of any which has ever lived. Both intentionally and inadvertently, humans have extended their mobility to a great number of other species, as well. Ships from Polynesian times (as long ago as 3500 BP) to the present have transported crop species and domesticated animals as well as stowaway rats and snakes. Recently, cargo ships have transported Zebra Mussels, Spiny Waterfleas, and Ruffe deep into the Great Lakes via ballast water. Europeans brought Purple Loosestrife and European Buckthorn to North America to beautify their gardens. Shakespeare enthusiast Eugene Schieffelin imported the now-ubiquitous European Starling to Central Park in the 1890s because he thought Americans should experience every bird mentioned in the works of Shakespeare. Australians imported the Cane Toad in an attempt to control the Cane Beetle, a native pest of sugar cane fields. The Brown Tree Snake (**Figure** 18.15) may have hitchhiked in the wheel-wells of military aircraft to Guam - and subsequently extirpated most of the island's "naïve" vertebrate species.

Figure 18.15: Many scientists consider exotic species to be the #2 cause of loss of biodiversity. One of the most infamous, the Brown Tree Snake (left), hitch-hiked on aircraft to Pacific Islands and caused the extinctions of many bird and mammal species which had evolved in the absence of predators. The Nile Perch (right) was intentionally introduced to Lake Victoria to compensate for overfishing of native species. The Perch itself overfished smaller species, resulting in the extinction of perhaps 200 species of cichlids.

Many of these **exotic** (non-native) **species**, away from the predation or competition of their native habitats, have unexpected and negative effects in new ecosystems. Freed from natural controls, introduced species can disrupt food chains, carry disease, out-compete natives for limited resources, or prey on native species directly - and lead to extinctions. Some hybridize with native species carefully tuned to local climate, predation, competition, and disease, resulting in **genetic pollution** which weakens natural adaptations. Others change the very nature of the habitats they invade; Zebra Mussels, for example, colonize most manmade and natural surfaces (including native mussels), filter-feeding so intensely that they increase water clarity and enrich bottom habitats with their waste.

Globalization and tourism are increasing the number of exotics which threaten biodiversity throughout the world, breaking down geographic barriers and threatening the wisdom of millions of years of evolution and natural selection. If current trends continue, our increasingly interconnected world will eventually be dominated by just a few fast-growing, highly adaptable, keenly competitive "super-species" rather than the rich diversity we have today. Some biologists, noting that invasive exotics closely resemble what we consider to be "weed" species, have concluded that the world's #1 weed species is – did you guess it? – none other than *Homo sapiens.*

Causes of Extinction #3: Overexploitation

The modern equivalent to overkill, **overexploitation** threatens fisheries, tropical rain forests, whales, rhinos, large carnivores and many other species. Practices such as clear-cutting old growth forests, strip mining, and driftnet fishing go beyond harvesting of single species or resources to degrade entire ecosystems. Technology-aided over-harvesting has reduced one of the richest fisheries in the world - the Grand Banks off the coast of Newfoundland – to an estimated 1% of what they were in 1977 (**Figure** 18.16). In 2003 in the journal *Nature,* Canadian biologists published an analysis of data showing that "industrialized" fishing has reduced large predatory fish worldwide by 90%. Some species' stocks are so depleted that less desirable species are illegally sold under the names of more expensive ones; in 2004, University of North Carolina graduate students tested DNA from fish sold as "red snapper" from eight states and found that different species made up 77% of the fish tested! Overexploitation happens on the level of genes and ecosystems as well as individual species. Forest plantations, fish hatcheries and farms, and intensive agriculture reduce both species diversity and genetic diversity within species.

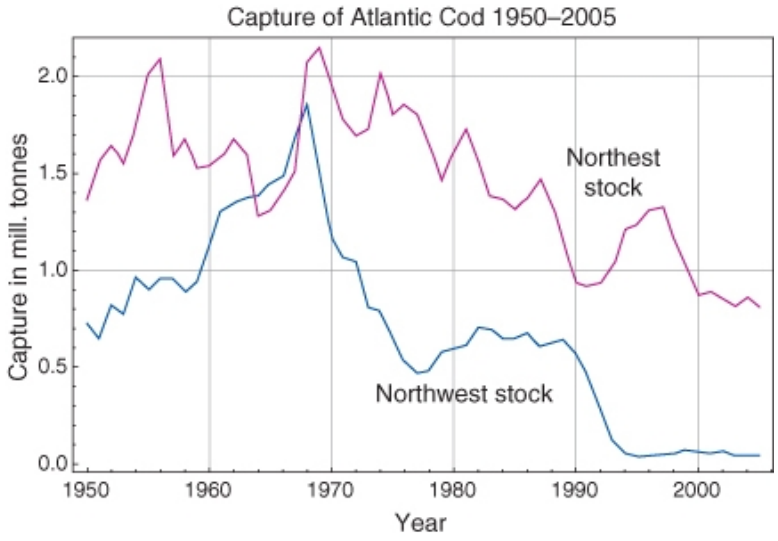

Figure 18.16: Overexploitation of Atlantic cod threatens one of the world's most productive fisheries: the Grand Banks off the coast of Newfoundland.

Causes of Extinction #4: Global Climate Change

Our increasing reliance on fossil fuels is altering the Earth's atmosphere and climate. The effects include acid rain, breaks in the ozone layer shielding us from ultraviolet radiation, and greenhouse gases which raise the Earth's air and ocean temperatures and sea levels. Burning tropical rain forests compounds the effect, releasing carbon as CO_2 and eliminating the forest's ability to **sequester** carbon – remove carbon as CO_2 from the atmosphere

- via photosynthesis. Inevitably, changing air and water temperatures, rainfall patterns, and salinity threaten species adapted to pre-warming conditions, and biodiversity declines globally. This concern is the topic of the Climate Change Lesson .

Causes of Extinction #5: Overpopulation

In 1960, Earth's human population stood at 3 billion. By 1999, we had grown to 6 billion. This unprecedented growth, together with developments in technology, has added immense pressure to resource and land use. Overpopulation compounds all of the aforementioned threats to biodiversity, and unequal distribution of resources extends the consequences to social and political instability. Human population growth continues (see the chapter on Biology of Populations). Growth rates vary – ominously, from a biodiversity perspective: the highest rates are in third world tropical countries where diversity is also highest. We have already seen how slash-and-burn agriculture and Lake Victoria fisheries connect socioeconomic changes to loss of biodiversity.

Causes of Extinction #6: Pollution

Pollution adds chemicals, noise, heat or even light beyond the capacity of the environment to absorb them without harmful effects on life. To a certain extent, pollution has not kept pace with population growth, at least in Europe and the US. Startling events such as the oil-and-debris-covered and lifeless Cuyahoga River catching fire in 1969 finally provoked the U.S. to stop viewing air and waterways as convenient dumping grounds for waste. Environmental legislation, including the establishment of the Environmental Protection Agency (EPA) has improved both water and air quality. Heeding the warning provided by the extirpation of the Peregrine Falcon from the Eastern U.S., scientists discovered that many synthetic chemicals concentrate as they move through the food chain (**biological magnification**), so that toxic effects are multiplied. DDT – the cause of the Peregrine's decline – was banned in the U.S., and regulation of pesticides was transferred from the Department of Agriculture to the EPA.

And yet, pollution continues to contribute to habitat degradation worldwide, especially in developing countries.

- **Air Pollution**: Knows no boundaries and growing concern about its effects on climate earn this topic two lessons later in this chapter. Acid rain, ozone depletion, and global warming each affect diversity.
- **Water Pollution**: Especially from threatens vital freshwater and marine resources in the US and throughout the world. Industrial and agricultural chemicals, waste, acid rain, and global warming threaten waters which are essential for all ecosystems. Threats to water resources are discussed in Lesson 2.
- **Soil Contamination**: Toxic industrial and municipal wastes, salts from irrigation, and pesticides from agriculture all degrade soils - the foundations of terrestrial ecosys-

tems and their biodiversity. These and other threats to soils are discussed in Lesson 2, Natural Resources.

Outside the developed world, pollution controls lag behind those of the U.S. and Europe, and developing nations such as China are rapidly increasing levels of pollution. Many pollution problems remain in industrialized countries, as well: industry and technology add nuclear waste disposal, oil spills, thermal pollution from wastewater, light pollution of the night skies, acid rain, and more to the challenges facing Earth's biodiversity. Many will be discussed in the following lesson on Natural Resources, and you can certainly research more about those which interest or concern you. Our next task will be to switch from the doomsday report of problems and causes to a discussion of what WE – ordinary citizens – can do to help protect Earth's biodiversity.

Protecting Biodiversity

Consider the following facts from the American Museum of Natural History's Center for Biodiversity and Conservation (AMNH-CBC) and the Environmental Protection Agency (EPA):

Every year, Americans:

- Throw away at least 2 billion disposable razors
- Discard enough paper and wood to heat 5 million homes for 200 years
- Drink more than two billion gallons of bottled water, costing 900 times more money than tap water – not counting the energy and toxics involved in packaging and shipping
- Retire up to 130 million cell phones, containing toxic metals such as arsenic, cadmium, and lead
- Generate about 3 million tons of toxic electronics waste (e-waste), and recycle only about 11%

Do any of these everyday experiences apply to you? You may be surprised to learn there is quite a lot you can do to help. Read carefully through the suggestions below, noting those that appeal to you strongly and those which seem most feasible. Many involve little more than awareness in decisions you already or will soon make.

Consume Thoughtfully and Wisely: Reduce Your Consumption Where Possible. Re-use, and Recycle. Make Durability and Efficiency Your Criteria for Product Purchases.

In general, when you buy:

- Buy locally whenever possible to reduce transportation costs for you and for the environment.
- Be aware of the natural resources used to make and transport any product you buy.
- Substitute other materials for plastics - which are made from petroleum and produce toxic waste.

Figure 18.17: Eat with the environment and your health in mind! In the United States, the Department of Agriculture (USDA) sets standards for organic products and certification. The green-and-white seal identifies products which have at least 95% organic ingredients. The program is helpful to consumers, but not without controversy (read Barbara Kingsolver's and/or Michael Pollan's).

- When you buy food plan your diet for your own health and that of the environment.
- Eat low on the food chain. Top carnivores get the least energy and the most poison.
- Buy local produce in season – to reduce transportation costs and the need for pesticides.
- Buy at farmers' markets or a Community Supported Agriculture (CSA) programs to support local farmers and reduce demand for energy-consuming and polluting large-scale agriculture and marketing.
- Choose organic produce - for your own health and to protect the environment from excessive nutrients and pesticides (**Figure** 18.17).

- ***When you buy fish for food or for your aquarium***
- Check to be sure that commercial species are not from overharvested areas,
- Verify that tropical saltwater fish were not collected using cyanide.

- ***When you need paper products,*** be sure they are made of recycled fiber.
- Or consider alternative materials such as hemp, kenaf, cornstarch, or old money or maps.
- Replace paper napkins and paper towels with cloth.
- Reuse envelopes and boxes. Wrap gifts in the comics or reusable cloth gift bags.

- ***When you buy products for cleaning,painting,or washing your car,***check the ingredients to be sure you are not exposing yourself and the environment to unnecessary toxins. Vinegar and baking soda work wonders!

- ***When you buy wood or wood products*** be sure harvesting followed **sustainable forest management** – practices which ensure future productivity, biodiversity, and ecosystem health.
- Look for SmartWood, FSC (Forest Stewardship Council) or similar labels.
- Consider recycled or salvaged wood.

When You Use Water, Remember Its Importance To All Life

- Check for water leaks and repair drips with new washers (**Figure** 18.18).
- Use low-flush toilets and low-flow faucets and shower heads.
- Have your tap water tested; use filters or refillable delivery if needed, rather than bottled water.

When You Must Use Energy, Consider Consequences and Choose Your Source Carefully

- Unplug electronic equipment such as fax machines, power tools, and anything connected to a remote control.
- Turn off power sources and lights when not in use.
- Use your bicycle, and support bike-friendly cities and roads.
- Walk! It's good for you, as well as the environment.
- Use public transportation, and support its expansion.
- Make energy-efficiency your #1 priority when you purchase appliances.
- Make fuel-efficiency your #1 priority if you purchase a car.
- Turn down your thermostat, especially at night. Just 2°F saves 500 pounds of greenhouse-inducing CO_2!

Figure 18.18: One drop per second from a dripping faucet wastes 2,700 gallons of water per year and adds to sewer and/or septic costs, as well.

- Weatherstrip and caulk doors and windows.
- Replace incandescent with fluorescent light bulbs, which are four times as efficient and last far longer.
- The EPA Energy Star Logo helps consumers to identify energy-efficient products. The less fossil fuel energy we use, the fewer greenhouse gases we release, reducing the threat of climate change.

Figure 18.19: Computer equipment becomes obsolete quickly and contains toxins such as lead and mercury. Consider donating your obsolete equipment, and if you must discard it, be sure you follow specific guidelines for recycling and hazardous waste disposal.

When You Must Dispose of Waste, Learn the Best Practice for Its Disposal

- Reduce or eliminate your use of plastic bags, sandwich bags, and six-pack plastic rings (and don't release balloons!) so that endangered sea turtles do not mistake these for their favorite food - jellyfish.
- Minimize and compost food waste.
- Recycle motor oil and unused paint.
- Use appropriate local hazardous waste facilities for recommended chemicals and medicines.
- Donate obsolete computers and other electronic equipment – or if you cannot, recycle such "e-waste" properly (**Figure** 18.19).

Don't Contribute to the Burgeoning Problem of Exotic Species

(The following points reference **Figure** 18.20.)

- Don't release aquarium fish, turtles, birds, or other pets into the wild.

Figure 18.20: Exotic (invasive or alien) species are often considered the #2 cause of extinction. Learn how to avoid transporting them!

- Clean your boat thoroughly after use, and avoid traveling with wild plants and animals.
- Your pet is also considered to be an exotic species. Don't let your pets hunt birds or wild animals.

Practice Sustainable Management on Your Own Land, Even If it is "Only" a Small Yard

- Minimize nonpoint source pollution by using organic or natural pesticides and fertilizers.
- Plant shade trees for air-conditioning and to absorb CO_2.
- Water plants and lawns in the evening.
- Better yet, use native and/or drought-tolerant plants for landscaping.
- Remember that City, County, State, and Federal lands are your lands, too. Get involved in local zoning and land use planning to ensure that development follows sustainable guidelines.

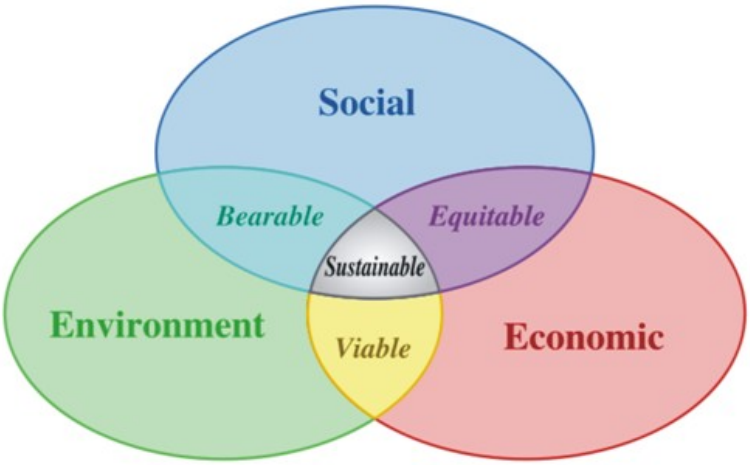

Figure 18.21: Sustainability as a goal in decision-making seeks the intersection of three sets of values. The environmental component includes maintaining ecosystem quality indefinitely.

Adopt and Spread Sustainable Perspectives and Philosophy

- Focus on diversity as a whole – genes, communities and ecosystems – rather than single "poster" species.
- Support the inclusion of ecosystems services in economic valuations.
- Encourage protection of areas large enough to accommodate migration, flooding, buffer zones, pollution from nearby development, and people and their activities.
- Realize that inequitable distribution of population, land, resources, education, and wealth threatens biodiversity.

- Promote the concept of sustainability as a guide for conservation decisions (**Figure** 18.21).
- Join philosophers and religious and community groups to explore environmental ethics.
- Help *everyone* understand basic ecology and the wealth of biodiversity shaped by billions of years of evolution.

Learn More!

- About the species with which you share the Earth.
- About local, national, and international threats to biodiversity
- About more solutions as they develop
- Jump in! Join local groups which monitor ecosystem health: Frog Watch, River Watch, or Bird Counts.
- Educate yourself about complex issues such as government subsidies and new technologies.
- Find out about local protected lands and volunteer your time and energy to restore native ecosystems.

Activate!

- Exercise your citizenship to protect biodiversity. Vote, communicate your views, and push for stronger environmental protection laws.
- Support organizations which promote national reserves, international treaties, and resource conservation.
- Support efforts by zoos, arboretums, museums and seed banks to help maintain genetic diversity through research, breeding, educational, and fundraising programs.

Lesson Summary

- Like all species, humans depend on land, water, air, and living resources for food, energy, clothing, and **ecosystem services** such as nutrient recycling, waste disposal, and renewal of soil, freshwater, and clean air.
- Unlike other species, human technology supplements "natural" energy resources with fossil fuels and exploits both biotic and abiotic resources and produces wastes beyond the biosphere's capacity for renewal.
- Biodiversity encompasses all variation in living systems, including genetic, species, and ecosystem diversity.
- Scientists do not know how many species currently inhabit the Earth; the vast majority of Bacteria and Archaea, Protists and Insects, are probably unknown. We discover new species of animals, plants, and fungi each year.

- About 1.8 million species have been identified, and most estimates of Earth's overall species biodiversity fall between 5 and 30 million.
- In general, biodiversity is highest near the equator, and decreases toward the poles.
- Biodiversity "hotspots" such as the California Floristic Province and unique habitats such as bogs occasionally disrupt the overall pattern.
- The fossil record and DNA analysis reveal a gradual increase in Earth's biodiversity after the first prokaryotes appeared roughly 4 billion years ago.
- Within the past 600 million years, a more detailed fossil record shows increasing biodiversity interrupted by five major extinctions in which at least 50% of species disappeared.
- According to a 1998 survey by the American Museum of Natural History, more than 70% of biologists consider the present era to be a sixth mass extinction event.
- Many scientists regard the Ice Age extinctions of large birds and mammals as the beginning of a continuum of extinctions caused by human activity which extends to the present.
- Dramatic losses of large mammal species follow a pattern of human dispersal across the globe from tens of thousands of years ago in Indonesia to just over 1,000 years ago in New Zealand, and over 20% of all bird species have become extinct within the past 1,100 years.
- Rates of extinction have accelerated in the past 50 years; current estimates include 3 species per hour and as many as 140,000 per year.
- In 2002, Harvard biologist E.O. Wilson predicted that if current rates of extinction continue, 50% of plant and animal species will be lost within the next 100 years – compared to hundreds of thousands or even millions of years for previous mass extinctions.
- Direct economic benefits include the potential to diversify our food supply, resources for clothing,shelter, energy, and medicines, a wealth of efficient designs which could inspire new technologies, models for medical research, and an early warning system for toxicity.
- Ecosystem services provided by biodiversity include ecosystem stability and productivity; maintaining and renewing soils, water supplies, and the atmosphere; nitrogen fixation and nutrient recycling; pollination, pest and disease control, and waste disposal.
- Less tangible but equally important are the cultural, aesthetic, and spiritual values and the importance of biodiversity to many modes of recreation.
- Finally, many people believe that biodiversity has intrinsic value, inherent in its existence.
- Human hunting, secondary effects on other species, disease carried and predation by exotic animals, and habitat destruction contributed to Ice Age extinctions.
- Habitat loss, including degradation and fragmentation, is the primary cause of extinction today; agriculture and deforestation continue to claim vegetated land and pollute both fresh and salt water seas.

1. Slash-and-burn agriculture is destroying tropical forest at rates which could result in

total loss by 2090.
2. In the U.S., agriculture has eliminated 50% of wetlands and 99% of tallgrass prairies.
3. Logging and development have destroyed more than 90% of Temperate Rainforest in the U.S.

- Exotic species disrupt food chains and entire ecosystems to contribute to extinction.
- The modern equivalent to overkill, overexploitation of economically important species and ecosystems, threatens fisheries, tropical rain forests, whales, rhinos, large carnivores and many other species.
- Global climate change caused by the burning of fossil fuels disrupts weather patterns and, as it has throughout Earth's history, holds the potential to force the extinction of carefully adapted species.
- Pollution of land, air, and water poisons life and destroys ecosystems.
- Between 1960 and 1999, the Earth's human population increased from 3 billion to 6 billion people. Overpopulation combined with unequal distribution of resources dramatically intensifies pressures on biodiversity.
- Our daily activities and decisions can significantly help to protect biodiversity.
- After reducing consumption and reusing and recycling, careful consumption can help to conserve ecosystems.

1. Local, seasonal products save energy costs for transportation.
2. Durable and efficient products reduce long-term resource consumption.

- Wise use of water resources helps to prevent desertification of ecosystems.
- Energy alternatives to fossil fuels reduce greenhouse gases, although nuclear energy has its own dangers.
- After minimizing waste, best practices for waste disposal ensure less pollution of ecosystems.
- The threats to biodiversity posed by exotic species mean that everyone should learn to avoid transporting them.
- Sustainable management of land, from small yards to local, state, and federal lands, conserves ecosystems.
- Sustainability as a guide for decision-making balances social, economic, and environmental values to structure human activities such that they can continue indefinitely.
- Learning about biodiversity and ecology is an important part of valuing and protecting the diversity of life.
- Voting, membership in conservation organizations, and working toward protective legislation can contribute to genetic, species, and ecosystem diversity.

Review Questions

1. Compare humans to other species in terms of resource needs and use and ecosystem service benefits and effects.
2. Define biodiversity and explain its three major components.
3. Give the three quantitative values for Earth's species diversity, and compare biodiversity across the Earth's surface and throughout the history of life.
4. Construct a chart showing why you consider biodiversity important. Your chart should include four categories (of the five presented in the chapter, or of your own choosing) and the 2-3 examples from each chapter that you consider most critical).
5. Analyze humans' role in extinctions by comparing the causes we think contributed to the Ice Age extinctions to the causes important to extinction today.
6. How might Tallgrass Prairies, the Brown Tree Snake, the Atlantic Cod, and the Peregrine Falcon serve as "poster species" to explain and highlight some of the causes of extinction?
7. "Reduce, Re-use, and Recycle" is so familiar to many people that it has lost much of its meaning. Yet it remains an efficient summary of the best conservation principles. Explain. Choose one new idea to add to these workhorses.
8. What two (or three) ecological principles can govern your food choices to help protect your health, biodiversity, and even global stability?
9. How does the concept of sustainable use differ from "reduce, re-use, and re-cycle"? How is it similar?
10. According to Barry Commoner, there are Four Laws of Ecology:

    - Everything is connected to everything else.
    - Everything must go somewhere.
    - Nature knows best.
    - There is no such thing as a free lunch.

    Explain how his laws govern the way nature does – and humans should – use energy and material resources in order to protect biodiversity.

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- http://www.biodiversityproject.org/biodiversity.htm
- http://ology.amnh.org/biodiversity/
- http://www.biodiversity911.org/
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- http://en.wikipedia.org

Vocabulary

air pollution Alteration of the Earth's atmosphere by chemical, particulate, or biological materials.

biodiversity hotspot A biogeographic region which has lost at least 70% of its original habitat, yet contains at least 1500 endemic species of vascular plants.

biodiversity Variation in life – at all levels of organization: genes, species, and ecosystems.

biological magnification (food chain concentration) The process in which synthetic chemicals concentrate as they move through the food chain, so that toxic effects are multiplied.

bionics Engineering which uses biological organisms' design principles to develop efficient products.

carbon sequestration Process which removes CO_2 from the atmosphere.

desertification Degradation of formerly productive land (usually at least semi-arid).

ecosystem diversity The variety of ecosystems on Earth.

ecosystem services Indirect benefits provided by ecosystem processes, such as nutrient cycling and waste disposal.

ecosystem A functional unit comprised of living things interacting with their nonliving environment.

endemic A unique species found only within a certain area and nowhere else.

epiphyte Plant which grows on top of another plant.

exotic (alien) species A species introduced either intentionally or unintentionally to a completely new ecosystem – a non-native species.

extirpation Elimination of a species from a particular region of its range.

genetic diversity Variation among individuals and populations within a species.

genetic pollution Hybridization or mixing of genes of a wild population with a domestic or feral population.

global warming The recent increase in the Earth's average near-surface and ocean temperatures.

greenhouse effect The trapping by the atmosphere of heat energy radiated from the Earth's surface.

keystone species Species having a functional importance to ecosystem diversity and stability which far outweighs its numerical or mass importance.

monoculture Large-scale cultivation of single varieties of single species.

natural resource Something supplied by nature which supports life, including sources.

pollution Release into the environment of chemicals, noise, heat or even light beyond the capacity of the environment to absorb them without harmful effects on life.

salination Increase in salt levels in soils.

species diversity The number of different species in an ecosystem or on Earth.

sustainable forest management Forest management which ensures that the goods and services yielded from a forest remain at a level that does not degrade the environment or the potential for similar levels of goods and services in the future.

sustainable use Use of resources at a rate which meets the needs of the present without impairing the ability of future generations to meet their needs.

Points to Consider

- Most of this lesson considered species and ecosystem diversity. Why is genetic diversity also very important?
- How does biodiversity in your area compare to the general global pattern of biodiversity? Give some reasons why it may or may not follow general trends.
- Choose one other area in which you are interested, and make the same comparison.
- Do you find the extinction statistics presented in this lesson alarming? Why do you think we don't hear more about the Sixth Extinction and the predicted loss of biodiversity?
- Which values of biodiversity do you feel are most compelling?
- Which solutions will you adopt in your daily life?

18.2 Lesson 18.2: Natural Resources

Lesson Objectives

- Distinguish between renewable and non-renewable resources.
- List the major energy and material resources upon which humans depend.
- Discuss the stresses increasing human consumption places on resource renewal.
- Sequence the events which lead to the formation of fossil fuels.
- Assess levels of depletion of non-renewable energy resources.
- Analyze the ways in which technology and consumption result in overharvesting, pollution, atmospheric changes, and habitat loss.
- Evaluate the effects of population growth on resource use and environmental pollution.
- Relate inequalities in resource distribution to global political stability.
- Compare the concept of sustainable use to that of renewable vs. nonrenewable resources.
- Describe the nature and uses of soil resources.
- Describe how human activities including technology affect ecosystem services such as

1. Soil generation
2. Waste disposal
3. Nutrient cycling
4. Recycling dead organic materials
5. Fertility of the land

- Discuss effects of population growth, technology, and consumption on land and soil resources.
- Relate soil erosion, pollution, and land development to ecosystem stability.
- Connect soil erosion, pollution, and land development to global stability.

- Evaluate the effects of changes in these services for humans.
- Review conflicts between agricultural technology, environment, and society.
- Recognize tradeoffs required by nuclear power plants: reduced emissions vs. radioactive fuels and waste.
- Analyze the ways in which humans have altered soil and land resources for other species.
- Identify the extent of terrestrial ecosystem loss, and its effects on biodiversity.
- Interpret the effects of soil pollution on biodiversity.
- Describe how human activities including technology affect ecosystem services such as:

1. The hydrologic cycle
2. Waste disposal
3. Nutrient cycling

- Evaluate the effects of changes in these services for humans.
- Discuss the effects of population growth, technology, and consumption on water resources.
- Explain the effects of overdrafting, pollution, and atmospheric changes on ecosystem stability.
- Relate overdrafting and pollution to global stability.
- Analyze the ways in which humans have altered water resources for other species.
- Identify the extent of wetland loss, and its effects on biodiversity.
- Interpret the effects of water pollution on biodiversity.

Introduction

Defining **natural resources** raises important philosophical questions.

"Resources" are useful or valuable. But are resources useful for and valuable to humans – or all life? If we "use" them, do we necessarily "consume" them? Is value limited to economics? Are resources limited to materials, or can they include processes, systems, and living things?

Definitions of "natural" go straight to the heart of our views about ourselves. Most definitions include a tension or conflict between the human and the non-human parts of the Earth: Anything that is natural is "not altered or disguised," "not produced or changed artificially," or, rather unhelpfully, "found in nature." We often define nature as separate from humans: "the world of living things and the outdoors" or with elements of inner conflict ("a primitive state of existence, untouched and uninfluenced by civilization or artificiality") or even religion ("humankind's natural state as distinguished from the state of grace").

It is not an idle exercise to think carefully about your own definition of natural resources, because such thinking can clarify your relationship and responsibilities to the Earth. Do natural resources exist only for humans to use (or "exploit" – a term repeated in many

definitions)? Are we apart from nature, or a part of nature? In what ways are we similar to other species? How are we different? How do those similarities and differences help us to define our responsibilities to "nature" – to other species and our physical environment?

Historically, the concept of natural resources was intended as a measure of respect and appreciation for the materials Earth provided, and the supplies humans used and modified to develop the civilization in which they lived. Economic value was primary, and a list of natural resources would include energy sources such as coal or oil and raw materials such as iron or copper. Living things could be, but often were not added: fibers from plants, and skins from animals.

As use became exploitation and later depletion, we began to better appreciate our dependence on natural resources, as well as our power over them. Economist E.F. Schumacher, in a 1973 series of essays titled *Small is Beautiful,* suggested that our economy is unsustainable because natural resources (especially energy) can be depleted. He made the case that natural resources should be considered capital, rather than expendable – *conserved,* rather than simply *used.* He also argued that nature's capacity to resist pollution is limited, pointing to the value of whole ecosystems and ecosystem services. During the 1990s, ecological economist Robert Constanza calculated that "nature's services" were worth $33 trillion per year – more than the $25 trillion total of the inter-human economy at that time. Although awareness of resource depletion and ecosystem services is increasing, their values remain inadequately recognized by our economy, and sustainability remains a goal for the future.

What definition for natural resources shall we use? On the Department of Energy's "Ask a Scientist" website, Bob Hartwell defines a natural resource as "something supplied by nature which supports life on this planet." This concise description includes most of the ideas we've discussed above, and views human use with an ecological perspective appropriate for the study of biology. Humankind is a part of nature, one species in an interdependent web which includes the Earth and all life. Without question, we are a unique species: we have the power to change that interdependent web in ways no other species can, we have the ability to learn about and understand the patterns and processes which maintain the web, and we have the responsibility to use our natural resources together with that understanding in ways which sustain the web – for our ourselves and for all life.

Most biologists today would probably classify ecosystems, their processes and "services," and their species as natural resources, together with energy sources and materials from the environment. **Biodiversity** (which includes both species and ecosystems) is certainly a natural resource, according to this definition. In this sense, this entire chapter explores natural resources. The first lesson dealt with biodiversity as well as some of the ecosystem services which depend on biodiversity. This lesson will focus on energy, land and soil, and water resources. Because several unique problems (acid rain and **ozone depletion**, for example) apply to atmospheric resources, we will focus on the atmosphere in a third lesson. A final lesson will combine our concerns about the closely related issues of energy use and atmospheric change to focus on **climate change**. These lessons will by no means address all natural resources, but they should give you an overview of the complexities of and need

for sustainable use, and provide you with some detailed insight into several major problems.

Renewable and Nonrenewable Resources: Energy and Sustainable Use

Applied to natural resources, **renewable** or **non-renewable** are relative rather than precise terms. Not surprisingly, we use human parameters to classify resources into these two categories.

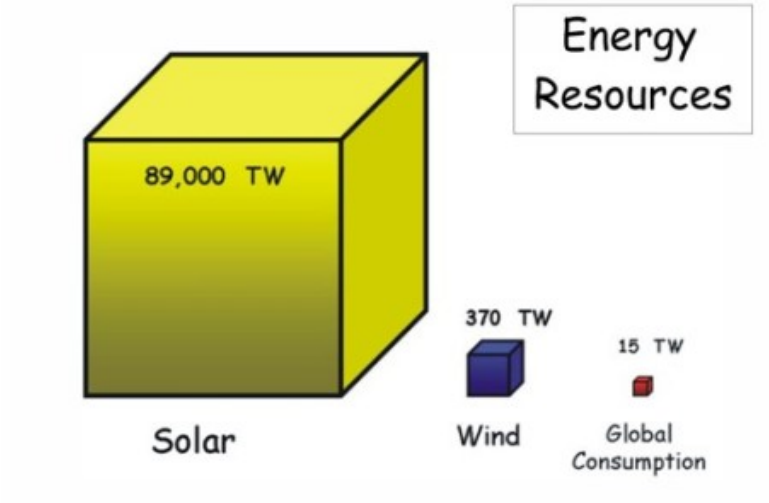

Figure 18.22: Solar radiation and wind energy are considered renewable resources because their availability far exceeds our rates of consumption. Here, availability is shown as volume equal to the annual flux in terawatts (1 TW = 10 watts). Eighty-nine thousand TW represents the amount of sunlight that falls on the Earth's surface, 370 TW depicts all the energy in the wind, and 15 TW was the global rate of energy consumption in 2004.

A resource replenished by natural processes at a rate roughly equal to the rate at which humans consume it is a **renewable resource**. Sunlight and wind, for example, are in no danger of being used in excess of their longterm availability (**Figures** 18.22, 18.23). Hydropower is renewed by the Earth's hydrologic cycle. Water has also been considered renewable, but overpumping of groundwater is depleting aquifers, and **pollution** threatens the use of many water resources, showing that the consequences of resource use are not always simple depletion. Soils are often considered renewable, but erosion and depletion of minerals proves otherwise. Living things (forests and fish, for example) are considered renewable because they can reproduce to replace individuals lost to human consumption. This is true only up to a point, however; overexploitation can lead to extinction, and overharvesting can remove nutrients so that soil fertility does not allow forest renewal. Energy resources derived from living things, such as ethanol, plant oils, and methane, are considered renewable, although their costs to the environment are not always adequately considered. Renewable

materials would include sustainably harvested wood, cork, and bamboo as well as sustainably harvested crops. Metals and other minerals are sometimes considered renewable because they are not destroyed when they are used, and can be recycled.

Figure 18.23: Wind power is considered a renewable resource because the rate of supply far exceeds the rate of use ( ). Although current use supplies less than 1% of the world's energy needs, growth in harvesting wind energy is rapid, with recent annual increases of more than 30 percent.

A **non-renewable resource** is not regenerated or restored on a time scale comparative to its consumption. Non-renewable resources exist in fixed amounts (at least relative to our time frame), and can be used up. The classic examples are fossil fuels such as petroleum, coal, and natural gas. Fossil fuels have formed from remains of plants (for coal) and phyto- and zoo-plankton (for oil) over periods from 50 to 350 million years. Ecologist Jeff Dukes estimates that 20 metric tons of phytoplankton produce 1 liter of gasoline! We have been consuming fossil fuels for less than 200 years, yet even the most optimistic estimates suggest that remaining reserves can supply our needs for

Oil: 45 years
Gas: 72 years
Coal: 252 years.

Nuclear power is considered a non-renewable resource because uranium fuel supplies are finite. Some estimates suggest that known economically feasible supplies could last 70 years at current rates of use - although known, and probably unknown reserves are much larger, and new technologies could make some reserves more useful.

Recall that the Second Law of Thermodynamics (which states that the entropy of an isolated system which is not in equilibrium will tend to increase over time) reinforces this view

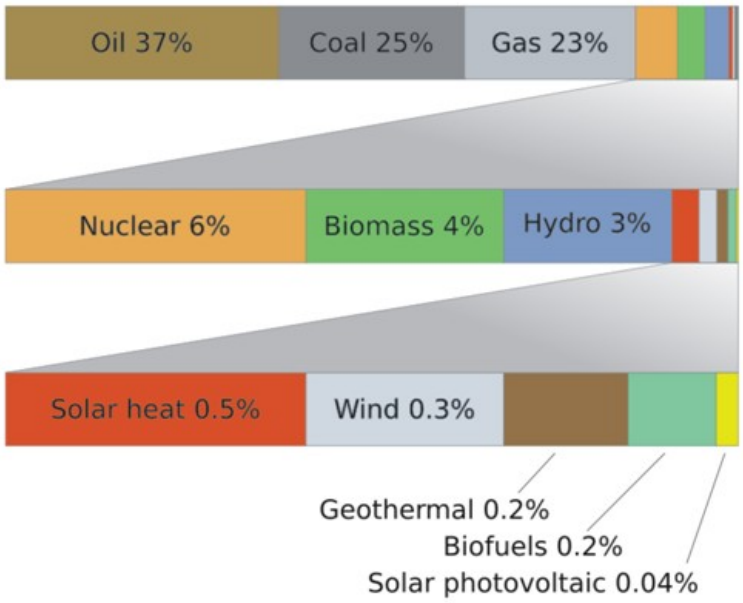

Figure 18.24: Global energy use includes mostly non-renewable (oil, coal, gas, and nuclear) but increasing amounts of renewable (biomass, hydro, solar, wind, geothermal, biofuels, and solar photovoltaic) resources.

of "renewable" and "non-renewable" resources: Energy flows downhill – gets used up, is transformed into heat; only materials that can be recycled are "renewable." It is only our time scale which makes any form of energy renewable. Eventually, the sun will burn out, as well.

Population growth, industrialization of developing countries, and advances in technology are placing increasing pressures on our rates of consumption of natural resources. Pollution and overexploitation foreshadow resource depletion, habitat loss, and atmospheric change. Unequal distribution of wealth, technology, and energy use (**Figure** 18.25) suggest that developing nations will further increase demands on natural resources. With these increases in demand, current levels of resource use cannot be maintained into the future, and social and political instability may increase. Improvements in technology could mitigate these problems to some extent.

The concept of renewable vs. non-renewable resources clearly depends on rates of human use (**Figure** 18.24); less clearly, its usefulness depends on the effects of use on other natural resources, such as pollution. Of course, we could change our rates of consumption. Indeed, if we increase our rate of consumption, renewable resources may need to be reclassified as non-renewable. This is the foundation of the concept of **sustainable use** – use of resources at a rate which meets the needs of the present without impairing the ability of future generations to meet their needs. Notice that this concept continues to focus on human needs; however, a solid understanding of ecology recognizes that human needs depend on entire ecosystems,

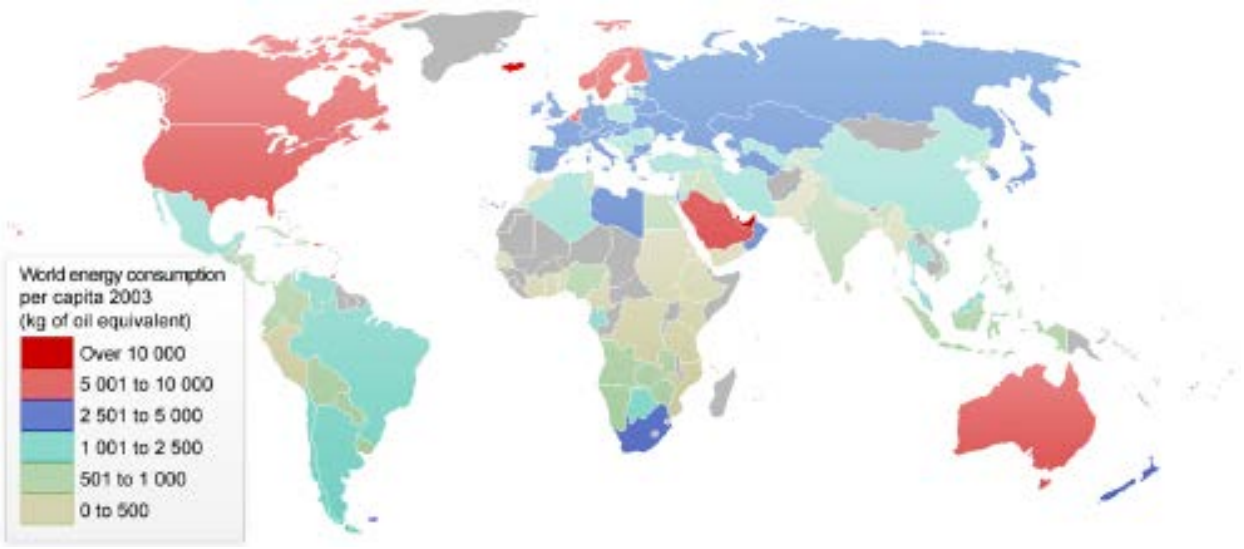

Figure 18.25: Per capita energy consumption illustrates the unequal distribution of wealth and natural resource use which threatens long-term resource supplies as developing nations demand higher standards of living. These inequalities threaten not only resource supplies but also global political stability.

which in turn depend on all species. Sustainable use could also apply to ecosystem services, which can be overwhelmed by overuse even though their "use" does not involve consumption. Perhaps we should shift our natural resource focus from rate of consumption (renewable vs. non-renewable) to sustainable use!

Soil and Land Resources

What negative connotations we give to soil resources in our daily conversation! Hands are "dirty;" clothing is "soiled." Yet the formation of soils require thousands and even millions of years of physical, geological, chemical, and biological processes. Soil's complex mixture of eroded rock, minerals, ions, partially decomposed organic material, water, air, roots, fungi, animals, and microorganisms supports the growth of plants, which are the foundation of terrestrial ecosystems (**Figure** 18.26). Soil is a balanced intersection of air, water, and land resources, sensitive to changes in any one element. We use soils for agriculture, gardening, landscaping, earth sheltered buildings, and to absorb waste from composting and septic drain fields. Peat, an accumulation of partially decayed plant material, can be burned for energy.

Soils can assimilate and remove low levels of **contamination**, thus it is useful for waste treatment. Not surprisingly, high levels of contamination can kill soil microorganisms, which help to accomplish this service. Toxics from industry, underground storage tanks, pesticide use, and leaching from landfills and septic tanks contaminate soils across the globe. Contaminated soils endanger human and ecosystem health.

Figure 18.26: Soil resources are a complex mixture of eroded rock, minerals, ions, partially decomposed organic material, water, air, roots, fungi, animals, and microorganisms, formed over thousands or even millions of years.

In 1980, after several years of health concerns and protests, the U.S. Government relocated and reimbursed 800 families from the Love Canal housing development built atop a landfill which had "disposed of" 22,000 tons of toxic waste from Hooker Chemical and Plastics Corporation. Increased awareness of the problems of abandoned toxic waste sites led to the passage later that year of **Superfund** legislation, which holds polluters accountable for effects of toxic waste, and taxes chemical and petroleum industries to pay for cleanup of sites where responsible parties cannot be identified. As of early 2007, the EPA listed 1,245 Superfund sites; 324 are delisted, and 66 new sites are proposed. In general, developing countries lag behind in identification, cleanup, and prevention.

Agriculture, as one of the largest land uses, has altered soils in a number of ways. When we harvest crops repeatedly from soil, we remove basic ions such as Calcium, Magnesium, Potassium, and Sodium. One result is **acidification**, which lowers soil fertility and productivity. **Acid rain** and the use of nitrogen fertilizers accelerate acidification, and acid rain can increase soil contamination.

Irrigation can degrade soils through **salination** – the accumulation of salts. High concentrations of salt make it difficult for plants to absorb water by osmosis, so salination reduces plant growth and productivity, and can lead to **desertification** (degradation of formerly productive land – usually at least semi-arid) and **soil erosion**.

Agriculture, deforestation, overgrazing, and development can remove vegetation to cause unnatural levels of erosion by wind and water. In the U.S., erosion forced its way into public

awareness during the 1930s after drought compounded exposed soils. The famous Dust Bowl (**Figure** 18.27) resulted in the loss of at least 5 inches of topsoil from nearly 10 million acres of land and the migration of 2.5 million people out of the Great Plains. Today in the U.S., contour plowing, cover crops, terracing, strip farming, no-till farming, reforestation, and better construction practices prevent some soil erosion (**Figure** 18.28), but the USDA reports that 1.6 billion metric tons of topsoil were lost annually between 1997 and 2001. Since Great Plains agriculture began some 200 years ago, the U.S. has lost one-third of its topsoil. Alarming rates of slash-and-burn agriculture in tropical forests expose thin soils to erosion, and development in China sends 1.6 billion tons of sediment annually into the Yellow River.

Figure 18.27: Soil erosion in the U.S. peaked during the Dust Bowl years of 1933-1939. Intense dust storms (left) shifted vast quantities of unprotected rich prairie soil (right) – much of it all the way into the Atlantic Ocean.

Figure 18.28: Conservation practices such as terracing, contour plowing and conservation buffers (left) and conservation tillage (right) prevent soil erosion and improve water quality.

With – or sometimes without – its soil, **land resources** are used by humans for agriculture, forestry, mining, industry, waste disposal, and cities. Modification of land for these uses inevitably alters ecosystems, and in many cases, the resulting urban sprawl, pollution, salination, erosion, and/or desertification lead to the loss of species, as well. As you learned in the lesson on biodiversity, habitat loss is the primary cause of extinction. Within the past 100 years, the area of land cultivated worldwide has increased 74%; grazing land increased

113%. Agriculture has cost the United States 50% of its wetlands and 99% of its tallgrass prairies. Land changes also result in fragmentation, yet another threat to biodiversity. Pressures from population growth cause the loss of land for human use, as well: ecologist David Pimental reports that erosion and salination destroy more than 2 million acres of prime agricultural land each year, and urban growth, transportation systems, and industry remove a million additional acres from production. Global increases in cropland and pasture from 1700 to 1990 are shown in **Figure** 18.29.

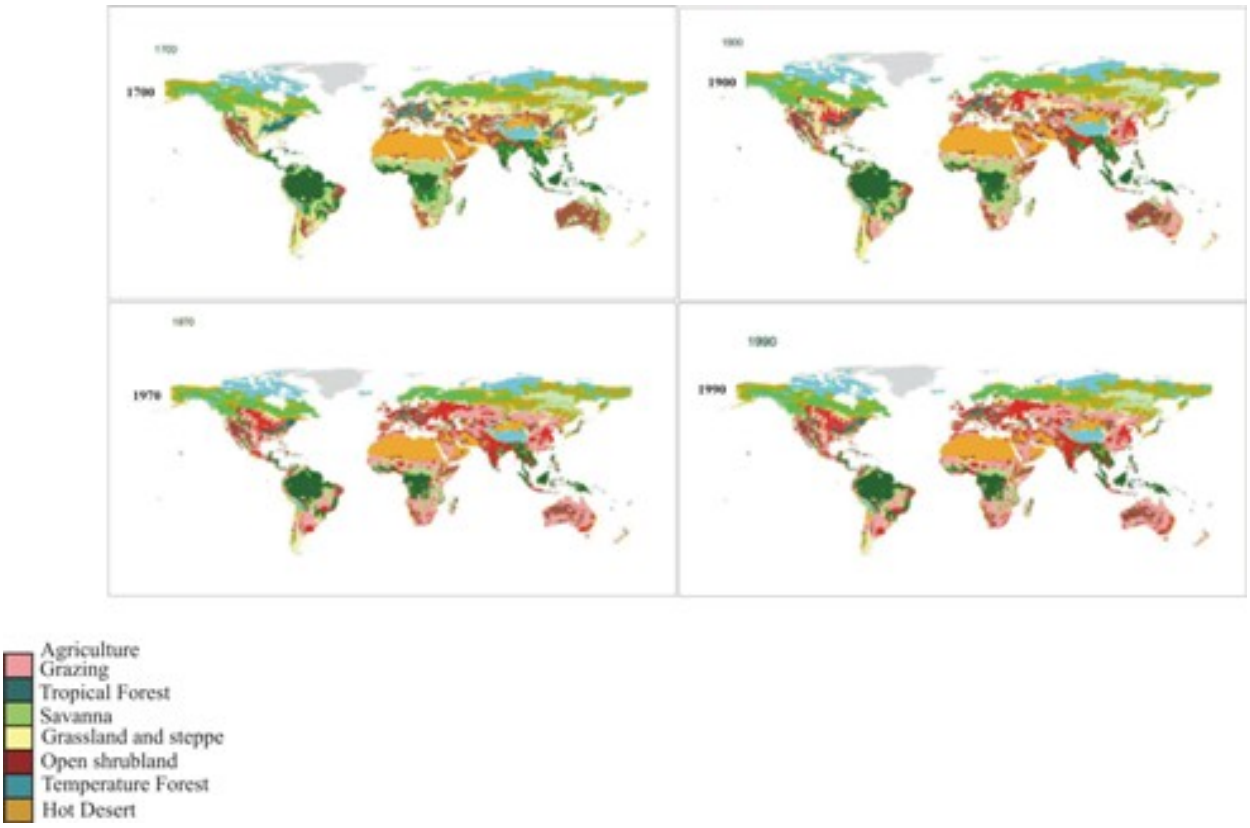

Figure 18.29: Changes in land use from 1700 to 1990 show the conversion of forests, grasslands, steppes, shrubland, and savannas to cropland (red) and grazing (pink).

Land use changes affect global processes as well as the ecosystems they directly involve. Deforestation – even if it is replaced by agriculture – reduces photosynthesis, which means that less CO_2 is removed from the atmosphere. The result is that CO_2 builds up – and as you will see in the fourth lesson of this chapter, an increase in CO_2 means an increase in the **greenhouse effect** and **global warming**. The International Panel on Climate Change (IPCC) estimates that land use change contributes 1.6 gigatons of carbon (as CO_2) per year to the atmosphere. This is highly significant when compared to the better-known fossil fuel-burning carbon contributions of 6.3 gigatons.

Urbanization and industry contribute to yet another land use issue that affects water re-

sources and the atmosphere. Increasingly, impervious surfaces such as parking lots, building roofs, streets and roadways are covering land areas. Impervious surfaces prevent water infiltration and groundwater recharge, increasing runoff and altering waterways. They deprive tree roots of aeration and water, decreasing productivity and increasing CO_2. Far more than vegetated surfaces, they absorb solar radiation and convert it to heat, increasing runoff, which eventually degrades streams. In the U.S., impervious surfaces cover an area almost as large as the state of Ohio. Solutions to this harmful impact include the development of porous pavements and green roofs (**Figure** 18.30).

Figure 18.30: Impervious surfaces (left) fragment habitats, increase runoff, degrade water sources, reduce photosynthesis, and effectively increase CO in the atmosphere. In the U.S., they cover an area of land almost the size of Ohio. Permeable pavements and green roofs (right) are beginning to reverse their effects.

Water Resources

At the intersection of land and water resources are **wetlands**: swamps, marshes and bogs whose soil is saturated (**Figure** 18.31). Historically, humans have viewed wetlands as wasted land; the U.S. has lost as much of 50% of its wetlands to agriculture, development, and flood control. Recently, wetland loss and the loss wetland species has taught us the importance of this ecosystem. Ecosystem services provided by wetlands include:

1. water storage and replenishment of aquifers
2. protection of coastlands from tides and storms
3. flood control
4. water purification I: slowing of water flow allows sedimentation to remove particulates
5. water purification II: denitrification of excess nutrients
6. rich habitat for wildlife
7. rich habitat for plants (30% of U.S. plant diversity)
8. recreation: hunting, fishing, ecotourism (e.g., The Everglades)

In the U.S., at least, recognition of the economic value and biodiversity of wetlands has led to restoration efforts and requirements for replacement of those lost through development.

The Ramsar "Convention on Wetlands of International Importance, especially as Waterfowl Habitat," signed by 18 nations in 1971, works to conserve wetlands throughout the world for their ecological services and their economic, scientific, cultural, and recreational values. Signatories today number 157, and they meet every 3 years.

Figure 18.31: Wetlands such as this area in Cape May, New Jersey, filter water both physically and chemically, protect coastal lands from storms and floods, and harbor an exceptional diversity of plants and animals.

Water is the quintessential resource of life; its unique physical, chemical and biological properties make it difficult for us to imagine life on any planet which lacks liquid water. For human use, however, water must be fresh. About 97% of Earth's water is found in the oceans. Of the 3% which is fresh water, over 2/3 is locked in ice. The 1% which is fresh liquid water is mostly below ground, leaving just 0.3% as surface water in lakes and rivers (**Figure** 18.32). The atmosphere contains just .001%.

As industry, agriculture, development, and a growing world population use more water, fresh water supplies are shrinking due to over-drafting of groundwater and pollution of surface and groundwater. Over-drafting has lowered water tables in Texas, California, and India, leaving many wells dry. New Orleans is below sea level, and San Jose, California dropped 13 feet, because over-pumping caused the land to subside. The UN and others have labeled the current state of water resources throughout the world a Water Crisis (**Figure** 18.33). You might wonder why we don't tap the oceans; the answer is that desalination is extremely costly in terms of energy and economics. The UN estimates that 1.1 billion people worldwide are without adequate fresh water, and that 2.6 billion lack enough water for sanitation to protect from disease. Water conflicts in the Middle East, Eastern Europe, and Korea have threatened regional political stability.

Water pollution, especially from **nonpoint sources** or runoff, threatens vital freshwater and marine resources in the U.S. and throughout the world. A single example dramatically

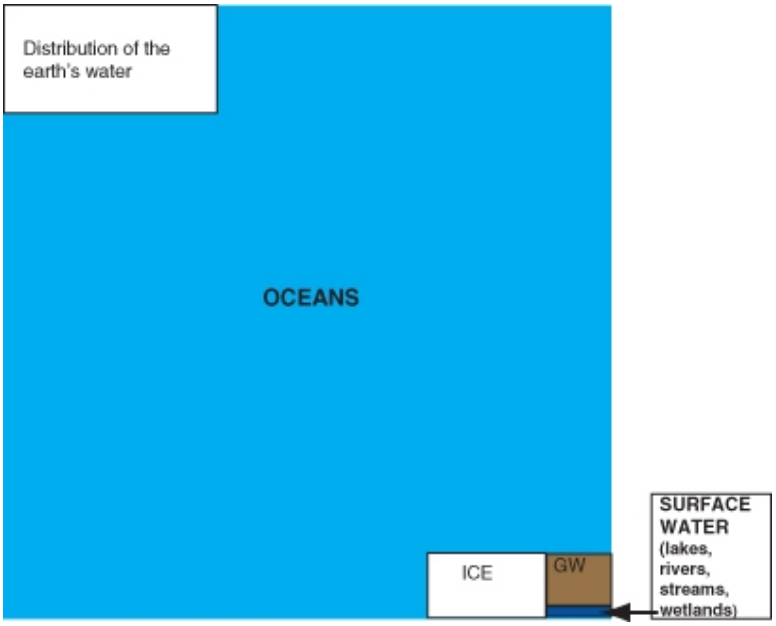

Figure 18.32: Earth is a watery planet, but only 3% is fresh water, and 2/3 of that is locked in ice. A little less than 1/3 is groundwater (GW), leaving 0.3% in surface water – the bright blue in the diagram above.

illustrates the potential for disruption of natural cycles and loss of biodiversity. Runoff of fertilizers applied to vast expanses of agricultural land and other sources such as wastewater have led to what ecologists say is a doubling of the amount of nitrogen available to plants and animals, and that amount could increase by another 60% by 2050. At first glance this may seem like a benefit to life, but it is not. Especially in aquatic ecosystems, excessive nutrients lead to overgrowth of algae, creating **algal blooms**. Some species are toxic in themselves, but more often, this **eutrophication** - literally, "feeding too well" - leads to such high levels of respiration (recall that photosynthesizers must respirate – especially at night!) that dissolved oxygen levels plummet, resulting in the death of fish and other species. Death results in decomposition and further nutrient input – compounding the problem. Eutrophication threatens one of the most diverse habitats on earth – coral reefs, which cover just 1% of the earth's surface yet harbor 25% (over 4000) - of marine fish species. Adapted to low-nutrient environments and characterized by tight nutrient cycles, reefs in the pathway of excess nutrient runoff from agriculture and development become overgrown with algae, which block light from coral polyps. The Nature Conservancy predicts that 70% of Earth's coral reefs will have disappeared by 2050 if current rates of destruction continue.

Among the most devastating consequences of eutrophication are at least 146 **dead zones**, where low oxygen levels caused by eutrophication have extinguished all ocean life. The most notorious extends into the Gulf of Mexico at the mouth of the Mississippi River, which brings fertilizer runoff from the U.S. corn belt (**Figure** 18.34). In July of 2007, this dead zone

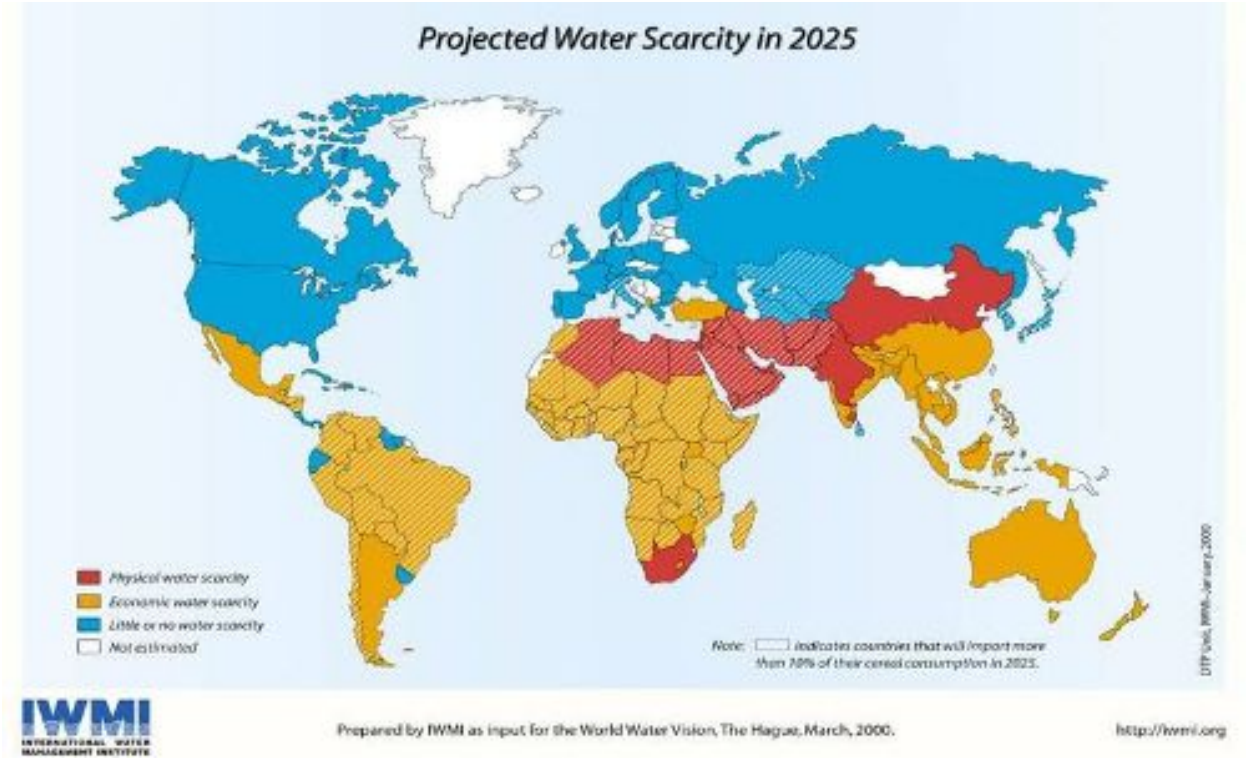

Figure 18.33: International Water Management Institute predicts expanding water shortages by 2025. The UN suggests a worldwide Water Crisis already exists. This map may oversimplify water problems; in the US, at least, drought and overdraft already threaten municipal and agricultural water supplies.

covered an area of ocean the size of New Jersey and affected shrimp and fishing industries as well as countless species of marine organisms. Interestingly, a similar zone in the Black Sea disappeared between 1991 and 2001, after political changes in the Soviet Union and Eastern Europe made fertilizers too expensive to use for most agriculture. Unfortunately, most are growing, and the nitrogen cycle disruption affects many bodies of freshwater throughout the world, as well.

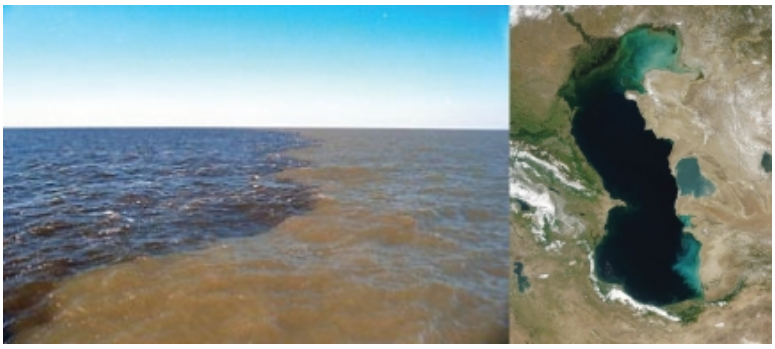

Figure 18.34: Eutrophication destroys marine and freshwater habitats and threatens biodiversity. Left: Nutrients and sediment flow from the Mississippi River watershed - into the Gulf of Mexico, creating a dead zone literally devoid of life. Right: A satellite photo of the Caspian Sea shows overgrowth of algae in the northern region where the Volga River brings excess nutrients from agricultural fertilizer runoff. Respiration by the algae and their bacterial decomposers lowers levels of dissolved oxygen so that most aquatic life dies.

Conserving Water and Other Natural Resources

Can you imagine what the expression **"virtual water"** could mean? It is an important concept in the conservation of water resources.

Virtual water is the water used in the production of a good or service. Although it is no longer contained in the product, its use is a part of the cost of production, and as such should be factored into the product's value. Here are some estimates of virtual water "contained" in various products, from the United Nations Education, Scientific, and Cultural Organization (UNESCO) Institute for Water Education:

- 1 kg wheat:1,300 liters
- 1 kg beef:15,000 liters
- 1 pair of jeans: 10,850 liters

The more water we use, the more likely we are to draw down wells and rivers beyond the hydrologic cycle's power to recharge them. The more water we use, the more we are likely to pollute the 1% of Earth's waters which are fresh (as well as the oceans). Protecting soils and

lands (especially wetlands and watersheds) is a critical part of protecting water resources, because the hydrologic cycle integrates terrestrial and aquatic ecosystems.

Thus, as for all conservation (wise use) or **sustainable use** (meeting needs of the present without impairing those of future generations), the first step is to reduce our use of water. This and other strategies to protect our water resources are summarized below. Don't forget the list of what you can do as an individual, at the end of the lesson on biodiversity!

1. Reduce the use of water, and the abuse of soil, land, and wetlands.

   - Landscape with native, drought-resistant vegetation.
   - Use low-flow toilets, faucets, and showerheads. Check out possible local government subsidies for installing these water saving mechanisms.
   - Purchase foods from water-efficient crops which do not require irrigation.

2. Reuse water where appropriate.

   - Gray water, which has been used for laundry or washing, can be used to water gardens or flush toilets.
   - On a municipal level, sewage water can be used for fountains, watering public parks or golf courses, fire fighting, and irrigating crops that will be boiled or peeled before consumption.

3. Catch runoff, which will also slow non-point source pollution and erosion.

   - Place rainbarrels adjacent to buildings.
   - Recharge pits which will re-fill aquifers.

4. Support legislation that reduces pollution.

   - For example in the U.S., the 1977 Clean Water Act, through the EPA, regulates industrial discharge of contaminants and sets standards for water quality.

5. Work locally, nationally and internationally to make clean fresh water available.

   - The United Nations Depart of Economic and Social Affairs has initiated a second Decade for Water for Life, 2005-2015 to increase awareness of water shortages and work toward sustainable use of freshwater resources.
   - The World Water Council unites 300 member organizations from 60 countries to work to "build political commitment and trigger action on critical water issues at all levels... to facilitate the efficient management and use of water …on an environmentally sustainable basis."

Lesson Summary

- One's definition of natural resources clarifies human relationships and responsibilities to the Earth.
- Robert Hartwell's definition defines natural resources as: "something supplied by nature which supports life on this planet." This definition includes ecosystems, ecosystem services, biodiversity, energy sources and raw materials.
- Renewable resources are replenished by natural processes as fast as, or faster than humans consume them.
- A non-renewable resource is not regenerated or restored on a time scale comparative to its consumption. Fossil fuels are a classic example of nonrenewable resources.
- In practice, pressure from growing populations and increasing industrialization can lead to overconsumption and/or degradation, changing a renewable resource into a non-renewable resource.
- According to the Laws of Energy, energy resources are not renewable because they get used up, but materials or matter is constant because it can theoretically be recycled.
- The concept of sustainable use – the use of resources at a rate which meets the needs of the present without impairing the ability of future generations to meet their needs – may be more helpful in decision making.
- The world's current energy use is unsustainable, especially if increases in developing countries are considered.
- Soils are complex mixtures which evolved over thousands of years to support terrestrial ecosystems.
- Humans use soils for agriculture, forestry, and waste disposal.
- Although soils have been considered renewable resources, human activities have changed them through:

1. Contamination with heavy metals and toxins
2. Acidification
3. Erosion
4. Salination
5. Conversion to cropland, cattle production, forestry, and urban centers

- Despite soil conservation practices, the U.S. continues to lose topsoil to erosion, and developing countries are losing even more.
- Land resources are used for agriculture, forestry, industry, mining, waste disposal, and urban areas.
- In the process of converting land resources, the U.S. has lost:

1. 99% of tallgrass prairies
2. at least 50% of wetlands
3. an area the size of Ohio to impervious surfaces

- Worldwide, conversion of forests to other uses, especially by slash-and-burn, adds CO_2 to the atmosphere and reduces the potential for absorption of CO_2 by photosynthesis, adding to greenhouse gases.
- Wetlands, greatly reduced because of earlier views that they were wasted land, provide many ecosystem services, including flood control, water purification, aquifer recharge, plant and wildlife habitat, and recreation.
- Liquid fresh water, the primary water resource for human use, comprises less than 1% of all water on Earth; most of this is groundwater.
- As industry, agriculture, development, and a growing world population use more water, fresh water supplies are shrinking due to over-drafting of groundwater and pollution of surface and groundwater.
- According to the United Nations, the current Water Crisis involves 1.1 billion people without adequate water supplies and 2.6 billion people who lack adequate water for sanitation.
- Agricultural fertilizer runoff and waste water add excess nutrients to surface waters, leading to algal blooms and eutrophication.
- Dead zones in coastal areas such as the Gulf of Mexico result from agricultural runoff from large areas of land. The dead zone at the mouth of the Mississippi River was the size of New Jersey in the summer of 2007.
- Virtual water is the water used in the production of a good or service.
- The more water we use, the more likely we are to overdraft aquifers and pollute water supplies.
- Concepts similar to virtual water highlight the importance of REDUCING USE as a first principle in conservation or sustainable use.
- A second principle is to REUSE resources. For water conservation, this can mean re-using gray water from laundry or showers for gardens or flush toilets.
- Legislation can set standards for water quality and limits on pollution.
- Local, national, and international organizations can work to promote awareness and encourage action.

Review Questions

1. Distinguish between renewable and nonrenewable resources, and relate these concepts to the Laws of Energy.
2. Classify the following resources as renewable or nonrenewable: coal, copper, iron, natural gas, nuclear power, oxygen, sunlight, water, wood, wool. Briefly explain your reasoning for each resource.
3. Describe the formation of soil, and classify it as a renewable or nonrenewable resource.
4. Compare and contrast land which has undergone desertification to ecosystems which harbor natural deserts. How can the apparently life-promoting act of irrigation eventually have the opposite effect?
5. We no longer experience the obvious tragedies associated with the Dust Bowl of the

1930s. Does this mean that soil erosion is no longer a significant problem?
6. Connect land use changes (e.g. forest to agriculture) to global warming. How important is this relationship?
7. List the ecosystem services of wetlands, and describe the extent of their loss.
8. Earth is the "water planet." Why are we threatened with a Water Crisis?
9. Explain why eutrophication – "too much a good thing" results in problems for aquatic life.
10. Analyze the disappearance of the Black Sea "dead zone" for its potential to help solve water pollution problems.

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- http://www.lifewater.org/
- http://www.amnh.org/exhibitions/water/
- http://www.smm.org/deadzone/
- http://www.sevengenerationsahead.org/about_us.html
- http://www.iisd.org/natres/
- http://en.wikipedia.org

Vocabulary

acid rain Precipitation in any form which has an unusually low pH.

algal bloom A rapid increase in the growth of algae, often due to a similar increase in nutrients.

anthropogenic sources Sources of pollution related to human activities.

biodiversity Variation in life – at all levels of organization: genes, species, and ecosystems.

biological magnification (food chain concentration) The process in which synthetic chemicals concentrate as they move through the food chain, so that toxic effects are multiplied.

dead zone Region of the ocean in which nutrient runoff and consequent eutrophication lower oxygen levels to the point at which life can no longer survive; less often applies to similar conditions in freshwater lakes.

desertification Degradation of formerly productive land (usually at least semi-arid).

ecosystem A functional unit comprised of living things interacting with their nonliving environment.

eutrophication An increase in nutrient levels in a body of water, often followed by an increase in plant or algae production.

global warming The recent increase in the Earth's average near-surface and ocean temperatures.

greenhouse effect The trapping by the atmosphere of heat energy radiated from the Earth's surface.

natural resource Something supplied by nature which supports life, including sources of energy and materials, ecosystems, and ecosystem services.

nonpoint source pollution Runoff of nutrients, toxins, or wastes from agricultural, mining, construction, or developed lands.

nonrenewable resource A resource which is not regenerated or restored on a time scale comparative to its consumption.

ozone depletion Reduction in the stratospheric concentration of ozone molecules, which shield life from damaging ultraviolet radiation.

point source pollution Single site sources of nutrients, toxins, or waste, such as industrial or municipal effluent or sewer overflow.

pollution Release into the environment of chemicals, noise, heat or even light beyond the capacity of the environment to absorb them without harmful effects on life.

primary pollutants Substances released directly into the air by processes such as fire or combustion of fossil fuel.

renewable energy sources Sources of energy which are regenerated by natural sources within relatively short time periods, e.g. solar, wind, and geothermal, as opposed to fossil fuels.

renewable resource A resource which is replenished by natural processes at a rate roughly equal to the rate at which humans consume it.

salination Addition of salts to soils, often by irrigation.

secondary pollutants Substances formed when primary pollutants interact with sunlight, air, or each other.

soil erosion Removal of soil by wind and water in excess of normal processes.

sustainable use Use of resources at a rate which meets the needs of the present without impairing the ability of future generations to meet their needs.

virtual water The water used in the production of a good or service.

wetland Swamps, marshes and bogs whose soil is saturated.

Points to Consider

- What is your own concept of natural resources? What relationship between humans and the Earth does it contain?
- Aldo Leopold wrote:"There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace." (http://en.wikiquote.org/wiki/Aldo_Leopold) Is your life close enough to "the farm" to recognize and fully appreciate the values of soil and of energy resources?
- Were you surprised by the virtual water data for beef or jeans? What other "virtual resources" are part of the products we consume?
- What kinds of legislation help to incorporate this level of water use in prices? What types of legislation prevent water use from being included in costs?
- Compare this statement from The Great Law of the Iroquois Confederacy to the contemporary concept of sustainable use: "In every deliberation we must consider the impact on the seventh generation... even if it requires having skin as thick as the bark of a pine." (http://en.wikipedia.org/wiki/Seven_generation_sustainability)

18.3 Lesson 18.3: Natural Resources II: The Atmosphere

Lesson Objectives

- Recognize that the Earth's atmosphere provides conditions and raw materials essential for life.
- Review the changes in the atmosphere over the history of the Earth.
- Describe the dynamic equilibrium which characterizes the natural atmosphere.

- Analyze the ways in which population growth, fossil fuel use, industrialization, technology, and consumption result in atmospheric changes.
- Explain the effects of these changes on ecosystems.
- Relate these effects to current global stability.
- Describe how human activities including technology affect ecosystem services such as:

1. nutrient cycling
2. hydrologic cycle
3. waste disposal

- Evaluate the effects of changes in these services for humans.
- Identify the ways in which humans have altered the air for other species.
- Relate air pollution to ecosystem loss.
- Interpret the effects of air pollution on biodiversity.
- Define acid rain.
- List the natural and anthropogenic causes of acid rain.
- Identify the effects of acid rain.
- Discuss solutions specific to the problem of acid rain.
- Locate and describe the origin of the ozone layer.
- Distinguish between ozone depletion and the ozone hole.
- Explain the role of ozone in absorbing ultraviolet radiation.
- Indicate the ways in which the ozone layer varies naturally.
- Discuss the relationship between recent changes in the ozone layer and human activities.
- Describe the measures taken to restore the ozone layer and evaluate their effectiveness.

Introduction

Air: so easy to take for granted. In its pristine state, we cannot see it, smell it, taste it, feel it, or hear it, except when the wind blows or clouds form. Yet its complex and dynamic mix of gases is essential for life. Nitrogen (78%) provides atoms which build proteins and nucleic acids via the nitrogen cycle. Oxygen (21%) permits the production of the ATP through cellular respiration, to power life. Carbon dioxide (.04%) provides the carbon for carbohydrate fuels and carbon skeletons to build life's bodies. Water (1-4% near the Earth's surface) has so many unique properties (adhesion, surface tension, cohesion, capillary action, high heat capacity, high heat of vaporization…and more) that it is difficult for us to imagine any form of life on any planet which does not depend on it. As a major component of the hydrologic cycle, the atmosphere cleans and replenishes Earth's fresh water supply, and refills the lakes, rivers, and oceans habitats for life (**Figure** 18.35). The Earth's atmosphere thins but reaches away from its surface for 100 kilometers toward space; between about 15 and 35 km lies the Ozone Layer – just a few parts per million which shields life from the sun's damaging Ultra-Violet radiation. Earth's atmosphere appears ideal for life, and indeed, as far as we know it is the only planetary atmosphere which supports life.

Figure 18.35: A composite photo of satellite images shows Earth and its life-supporting waters and atmosphere.

As we noted in the History of Life chapter, the Earth's atmosphere has not always been this hospitable for life. Life itself is probably responsible for many dramatic changes, including the addition of oxygen by photosynthesis, and the subsequent production of ozone from accumulated oxygen. Changes in CO_2 levels, climate, and sea level have significantly altered conditions for life, even since the addition of oxygen some 2 billion years ago. On a daily time scale, dramatic changes take place:

- most organisms remove O_2 and add CO_2 through cellular respiration
- most autotrophs remove CO_2 and add O_2 through photosynthesis
- plants transpire vast quantities of water into the air
- precipitation returns it, through gentle rains or violent storms, to the Earth's surface

On a human time scale, the daily dynamics balance, and the atmosphere remains at equilibrium – an equilibrium upon which most life depends.

Upsetting the Equilibrium of the Atmosphere: Air Pollution

Despite the atmosphere's apparent vastness, human activities have significantly altered its equilibrium in ways which threaten its services for life. Chemical substances, particulate matter, and even biological materials cause **air pollution** if they modify the natural characteristics of the atmosphere. **Primary pollutants** are directly added to the atmosphere by processes such as fires or combustion of fossil fuels (**Figure** 18.36). Secondary pollutants, formed when primary pollutants interact with sunlight, air, or each other, can be equally damaging. The chlorine and bromine which threaten the Ozone Layer are **secondary pollutants**, formed when refrigerants and aerosols (primary pollutants) decompose in the stratosphere (**Figure** 18.37).

Figure 18.36: Burning fossil fuels – by factories, power plants, home furnaces, and motor vehicles – is a major source of air pollution.

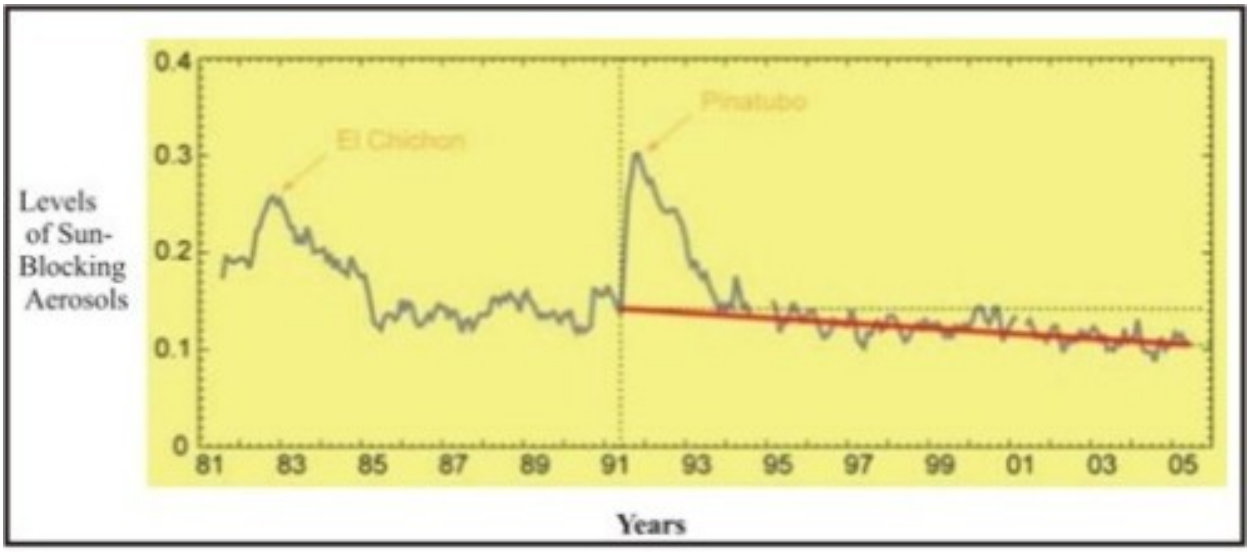

Figure 18.37: Levels of sun-blocking aerosols declined from 1990 to the present. A corresponding return to pre-1960 levels of radiation suggests that pollution control measures in developed countries have counteracted Global Dimming. However, particulates are still a problem in developing countries, and could affect the entire global community again in the future. Aerosol increases in 1982 and 1991 are the result of eruptions of two volcanoes, El Chichon and Pinatubo.

The majority of air pollutants can be traced to the burning of fossil fuels. We burn fuels in power plants to generate electricity, in factories to power machinery, in stoves and furnaces for heat, in airplanes, ships, trains, and motor vehicles for transportation, and in waste facilities to incinerate waste. Since long before fossil fuels powered the Industrial Revolution, we have burned wood for heat, fireplaces, and campfires and vegetation for agriculture and land management. The resulting primary and secondary pollutants and the problems to which they contribute are included in **Table** 18.2.

Table 18.2:

Pollutant	Example/Major Source	Problem
Sulfur oxides (SO_x)	Coal-fired power plants	Acid Rain
Nitrogen oxides (NO_x)	Motor vehicle exhaust	Acid Rain
Carbon monoxide (CO)	Motor vehicle exhaust	Poisoning
Carbon dioxide (CO_2)	All fossil fuel burning	Global Warming
Particulate matter (smoke, dust)	Wood and coal burning	Respiratory disease, Global Dimming
Mercury	Coal-fired power plants, medical waste	Neurotoxicity
Smog	Coal burning	Respiratory problems; eye irritation
Ground-level ozone	Motor vehicle exhaust	Respiratory problems; eye irritation

Beyond the burning of fossil fuels, other **anthropogenic** (human-caused) **sources** of air pollution are shown in **Table** 18.3.

Table 18.3:

Activity	Pollutant	Problem
Agriculture: Cattle Ranching	Methane (CH_4)	Global Warming
Fertilizers	Ammonia (NH_3), Volatile Organic Chemicals(VOCs)	Toxicity, Global Warming
Herbicides and Pesticides		Cancer
Erosion	Persistent Organic Pollutants(POP): DDT, PCBs, PAHs*	Global Dimming
	Dust	

Table 18.3: (continued)

Activity	Pollutant	Problem
Industry (solvents, plastics) Refrigerants, Aerosols	VOCs, POPs CFCs	Cancer, Global Warming Ozone Depletion
Nuclear power and defense	Radioactive waste	Cancer
Landfills	Methane (CH_4)	Global Warming
Mining	Asbestos	Respiratory problems
Biological Warfare	Microorganisms	Infectious Disease
Indoor Living	CO, VOCs, asbestos, dust, mites, molds, particulates	Indoor air pollution

- DDT = an organic pesticide; PCB = poly-chlorinated biphenyls, used as coolants and insulators; DDT and most PCBs are now banned at least in the U.S., but persist in the environment; PAHs = polycyclic aromatic hydrocarbons – products of burning fossil fuels, many linked to health problems

Many pollutants travel indoors in building materials, furniture, carpeting, paints and varnishes, contributing to indoor air pollution. In 2002, the World Health Organization estimated that 2.4 million people die each year as a consequence of air pollution – more than are killed in automobile accidents. Respiratory and cardiovascular problems are the most common health effects of air pollution, but accidents which release airborne poisons (the nuclear power plant at Chernobyl, the Union Carbide explosion in Bhopal, and the "Great Smog of 1952" over London) have killed many people – and undoubtedly other animals – with acute exposure to radiation or toxic chemicals.

If you study the problems caused by air pollution (third column in the tables, above), you will note that beyond human health, air pollution affects entire **ecosystems**, worldwide. **Acid Rain, Ozone Depletion**, and **Global Warming** are widespread and well-recognized global concerns, so we will explore them in detail in independent sections of this lesson, – and an entire lesson on Global Warming. Effects of toxins, which poison wildlife and plants as well as humans, were addressed in discussions of soil and water pollution in the last chapter. Before we move on to the "Big Three," let's take a brief look at the problems caused by particulates and aerosols, since these are unique pollutants of air, rather than soil or water.

"Global dimming" refers to a reduction in the amount of radiation reaching the Earth's surface. Scientists observed a drop of roughly 4% between 1960 and 1990, and attributed it to particulates and aerosols (in terms of air pollution, **aerosols** are airborne solid particles or liquid droplets). These pollutants absorb solar energy and reflect sunlight back into space. The consequences for life are many:

- Less sunlight means less photosynthesis.
- Less photosynthesis means less food for all trophic levels.
- Less sunlight means less energy to drive evaporation and the hydrologic cycle.
- Less sunlight means cooler ocean temperatures, which may lead to changes in rainfall, drought and famine.
- Less sunlight may have cooled the planet, masking the effects of Global Warming.

Recent measurements of sunlight-absorbing particulates show a decline since 1990, which corresponds to a return to normal levels of radiation (**Figure** 18.37). These data suggest that Clean Air legislation enacted by developed nations may have improved air quality and prevented most of the above effects, at least for now. Two caveats remain:

1. If "Global Dimming" did indeed mask Global Warming for 30 years, predictions about future climate change may be too conservative. Keep this in mind when we address Global Warming in the next lesson.
2. Population growth and industrialization of developing countries continues to increase levels of **pollution**.

Massive waves of pollution from Asian industry have blown across the Pacific by prevailing winds (**Figure** 18.38). On some days, atmospheric physicists at the Scripps Institution of Oceanography have traced nearly one-third of the air over Los Angeles and San Francisco directly to Asian sources. The waves are made of dust from Asian deserts combined with pollution from increasing industrialization, making the level of particulates and aerosols in Beijing, for example, reach levels 7 times World Health Organization standards. Scientists estimate that the clouds may be blocking 10% of the sunlight over the Pacific. By seeding clouds, the aerosols and particulates may be intensifying storms. In addition to direct effects on the global atmosphere (such waves can circle the Earth in three weeks), these pollution clouds can, as we stated above, mask Global Warming.

One additional topic relates to atmospheric change. **Light pollution** (**Figure** 18.39) results from humans' production of light in amounts which are annoying, wasteful, or harmful. Light is essential for safety and culture in industrial societies, but reduction in wasteful excess could mitigate its own harmful effects, as well as the amounts of fossil fuel used to generate it. Astronomers – both amateur and professional – find light interferes with their observations of the night skies. Some studies show that artificial spectra and excessive light exposure has harmful effects on human health. Life evolved in response to natural cycles and natural spectra of light and dark, so it is not surprising that our changes in both of those might affect us and other forms of life. Light pollution can affect animal navigation and migration and predator/prey interactions. Because many birds migrate by night, Toronto, Canada has initiated a program to turn out lights at night during spring and fall migration seasons. Light may interfere with sea turtle egg-laying and hatching, because both happen on coasts at nighttime. The behavior of nocturnal animals from owls to moths can be changed by light,

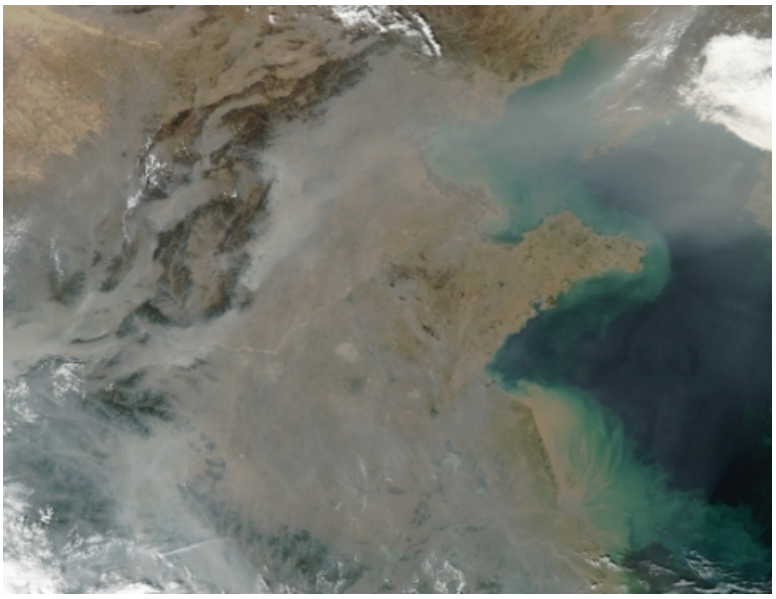

Figure 18.38: A cloud of smoke and haze covers this region of China from Beijing (top center) to the Yangtze River (bottom right). At the top right, pollution is blowing eastward toward Korea and the Pacific Ocean. Aerosol pollution with large amounts of soot (carbon particles) is changing precipitation and temperatures over China. Some scientists believe that these changes help to explain increasing floods and droughts.

and night-blooming flowers can be affected directly or through disruption of pollination. Zooplankton normally show daily vertical migration, and some data suggests that changes in this behavior can lead to **algal blooms**.

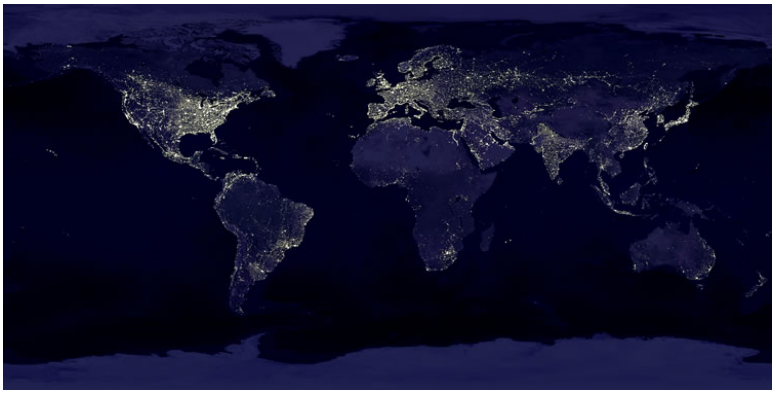

Figure 18.39: When light produced by humans becomes annoying, wasteful, or harmful, it is considered light pollution. This composite satellite image of Earth at night shows that light is concentrated in urban – but not necessarily population – centers. The U.S. interstate highway system, the Trans-Siberian railroad, and the Nile River are visible at higher magnifications.

Solutions to problems caused by light pollution include

- reducing use
- changing fixtures to direct light more efficiently and less harmfully
- changing the spectra of light released
- changing patterns of lighting to increase efficiency and reduce harmful effects

Many cities, especially those near observatories, are switching to low-pressure sodium lamps, because their light is relatively easy to filter.

Acid Rain

Do you remember the pH scale? Its range is 0-14, and 7 is neutral – the pH of pure water. You've probably measured the pH of various liquids such as vinegar and lemon juice, but do you know how important even very small changes in pH are for life? Your body maintains the pH of your blood between 7.35 and 7.45, and death results if blood pH falls below 6.8 or rises above 8.0. All life relies on relatively narrow ranges of pH, because protein structure and function is extremely sensitive to changes in concentrations of hydrogen ions. An important pollution problem which affects the pH of Earth's environments is **Acid Rain** (**Figure** 18.40).

Rain, snow, fog, dew, and even dry particles which have an unusually low pH are commonly considered together as **Acid Rain**, although more accurate terms would be acid precipitation or acid deposition. You will remember that a pH below 7 is acidic, and the range between 7 and 14 is basic. Natural precipitation has a slightly acidic pH, usually about 5, mostly because CO_2, which forms 0.04% of the atmosphere, reacts with water to form carbonic acid:

Table 18.4:

CO_2	$+ H_2O$	H_2CO_3	HCO_3^-	$+ H^+$
carbon dioxide	water	carbonic Acid	bicarbonate	hydrogen ion

This natural chemical reaction is actually quite similar to the formation of acid rain, except that levels of the gases which replace carbon dioxide are not normally significant in the atmosphere. The most common acid-forming pollutant gases are oxides of nitrogen and sulfur released by the burning of fossil fuels. Because burning may result in several different oxides, the gases are often referred to as "NO_x and SO_x." This may sound rather affectionate, but it's more accurate to think of it as obNOXious! Whereas the carbonic acid formed by carbon dioxide is a relatively weak acid, the nitric and sulfuric acids formed by NO_x and SO_x are strong acids, which ionize much more readily and therefore cause more damage. The reactions given below slightly simplify the chemistry (in part because NO_x and SO_x are complex mixtures of gases), but should help you see the acidic results of an atmospheric mixture of water and these gases.

Table 18.5:

NO_2	$+ OH^-$	$\rightarrow HNO_3$	NO_3^-	$+ H^+$
nitrogen dioxide	hydroxide ion (from water)	nitric Acid	nitrate	hydrogen ion

Table 18.6:

SO_3	$+ H_2O$	$\rightarrow H_2SO_4$	SO_4^{-2}	$+ 2H^+$
sulfur trioxide	water	sulfuric acid	sulfate	hydrogen ions

Nitrogen and sulfur oxides have always been produced in nature by volcanoes and wildfires and by biological processes in wetlands, oceans, and even on land. However, these natural levels are either limited in time or amount; they account for the slightly acidic pH of "normal" rain. Levels of these gases have risen dramatically since the Industrial Revolution began; scientists have reported pH levels lower than 2.4 in precipitation in industrialized areas.

Generation of electricity by burning coal, industry, and automobile exhaust are the primary sources of NO_x an SO_x. Coal is the primary source of sulfur oxides, and automobile exhaust is a major source of nitrogen oxides.

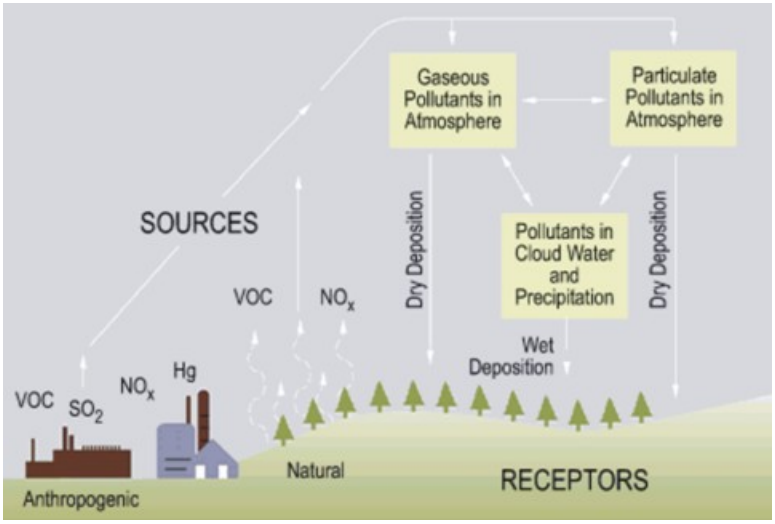

Figure 18.40: formation begins when nitrogen and sulfur oxides (here NO and SO) and volatile organic compounds (VOC) from burning fossil fuels escape into the atmosphere. When these gases or particulates combine with water – either in the atmosphere or after reaching the ground – they become acid deposition. The term acid rain commonly refers to all forms of acid deposition.

Because most life requires relatively narrow pH ranges near neutral, the effects of acid rain can be devastating. In soils, lowered pH levels can kill microorganisms directly, altering decomposition rates, nutrient cycles, and soil fertility. A secondary effect of increased acidity is the leaching of nutrients, minerals, and toxic metals such as aluminum and lead from soils and bedrock. Depletion of nutrients and mobilization of toxins weakens trees and other plants, especially at higher altitudes where higher precipitation and acid fog damage leaves and needles, as well (**Figure** 18.41).

The flow of acid rain through watersheds increases acidity, nutrients, and toxins in aquatic ecosystems. Fish and insects are sensitive to changes in pH, although different species can tolerate different levels of acidity (**Figure** 18.42). Food chain disruption can compound even slight changes in pH; for example, acid-sensitive mayflies provide food for less-sensitive frogs. Additional nitrates in aquatic systems can lead to **eutrophication** and **algal blooms**, discussed in the last lesson.

The sensitivity of lakes, streams, and soils to damage from acid rain depends on the nature of the soils and bedrocks. Watersheds containing limestone, which can buffer (partially neutralize) the acid, are less severely affected. In addition, northern regions with long winters suffer "acid shock" when spring thaws dump months of accumulated acid precipitation into

Figure 18.41: A mountain forest in the Czech Republic shows effects attributed to acid rain. At higher altitudes, effects on soils combine with direct effects on foliage of increased precipitation and fog.

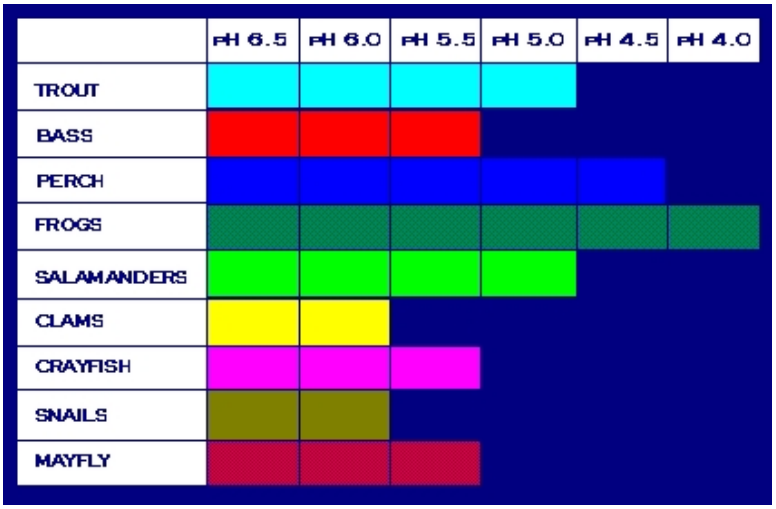

Figure 18.42: Aquatic species show varying sensitivity to pH levels. Colored bars show survival ranges. Trout are more sensitive to increasing acidity than frogs, but mayflies, which frogs consume, are even more sensitive. Consequently, changes in a lake's acidity may affect ecosystems more severely than simple species sensitivity charts would indicate.

streams and rivers. In the US, lakes and streams in the Appalachians, northern Minnesota and upper New York, and Western mountains have been more severely impacted by acid rain. According to the EPA, the pH of Little Echo Pond in New York state, 4.2, is one of the lowest in the U.S.

Another class of victims of acid rain is entirely within the realm of human culture and history. Acid's ability to corrode metal, paints, limestone, and marble has accelerated erosion of buildings, bridges, statues, monuments, tombstones, and automobiles (**Figure** 18.43).

Figure 18.43: Acid rain accelerates erosion of statues, monuments, buildings, tombstones, bridges, and motor vehicles.

Attempts to solve the problem of acid rain began with building taller smokestacks. These only sent the polluting gases higher into the atmosphere, relieving local problems temporarily, but sending the damage to areas far from their industrial sources. Today in the U.S. and other western nations, smokestacks increasingly use "scrubbers" which remove as much as 95% of SO_x from exhausts; the resulting sulfates "scrubbed" from the smokestacks can sometimes be sold as gypsum (used in drywall, plaster, fertilizer and more), but may also be landfilled. Catalytic converters and other emission control technologies remove NO_x from motor vehicle exhaust. However, population growth and development throughout the world is increasing pressures to use more fossil fuels and high-sulfur coal, often without these expensive technologies.

Ozone Depletion

Many people confuse the "hole in the ozone" with "global warming." Although the two are related in part, they are separate problems with separate effects and only partially overlapping causes, so they require separate solutions.

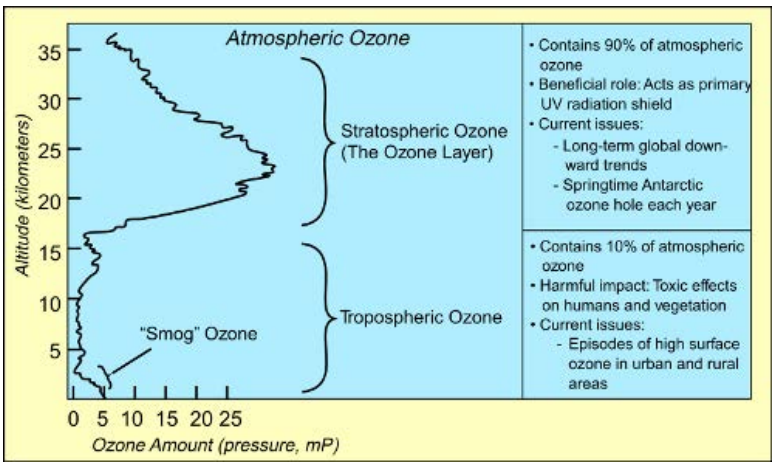

Figure 18.44: At altitudes less than 5 kilometers, respiratory irritant "smog" ozone forms when sunlight reacts with pollutants. The Ozone Layer, at altitudes between 15 and 35 kilometers, forms when UV radiation interacts with oxygen, and shields life on Earth from 97-99% of the Sun's damaging UV radiation.

Ozone is both a threat and a gift (**Figure** 18.45). As a ground-level product of the interaction between sunlight and pollutants, it is considered a pollutant which is toxic to animals' respiratory systems. However, as a component of the upper atmosphere, it has shielded us and all life from as much as 97-99% of the sun's lethal UV radiation for as long as 2 billion years. The "hole" in the ozone develops in this thin upper **Ozone Layer**. How long will that protection continue? Let's explore the problem of ozone depletion.

The Ozone (O_3) Layer forms when UV radiation strikes oxygen molecules (O_2) in the stratosphere, between 15 and 35 kilometers above the Earth's surface. Even the highest concentrations of ozone are only about 8 parts per million, but ever since photosynthesis oxygenated the Earth's atmosphere, allowing ozone-forming chemical reactions, this thin Ozone Layer has shielded life from the mutagenic effects of ultraviolet radiation – especially the more damaging UV-B and UV-C wavelengths (**Figure** 18.44).

The thickness of the Ozone Layer varies seasonally and across the Earth – thicker in Spring than in Autumn, and at the Poles compared to near the Equator. **Ozone depletion** describes two related declines in stratispheric ozone. One is loss in the total amount of ozone in the Earth's stratosphere – about 4% per year from 1980 to 2001 (**Figure** 18.47). The second, much larger loss refers to the **ozone hole** – a seasonal decline over Antarctica (**Figures** 18.48 and 14), which has now lost as much as 70% of pre-1975 ozone levels. A much smaller "dimple" overt the North Pole has also shown a 30% decline. The Antarctic ozone hole occasionally affects nearby Australia and New Zealand after annual breakup. A secondary effect is the decline in stratosphere temperatures, because when ozone absorbs UV radiation, it is transformed into heat energy.

The causes of ozone depletion are gases which unbalance the ozone cycle (**Figure** 18.46)

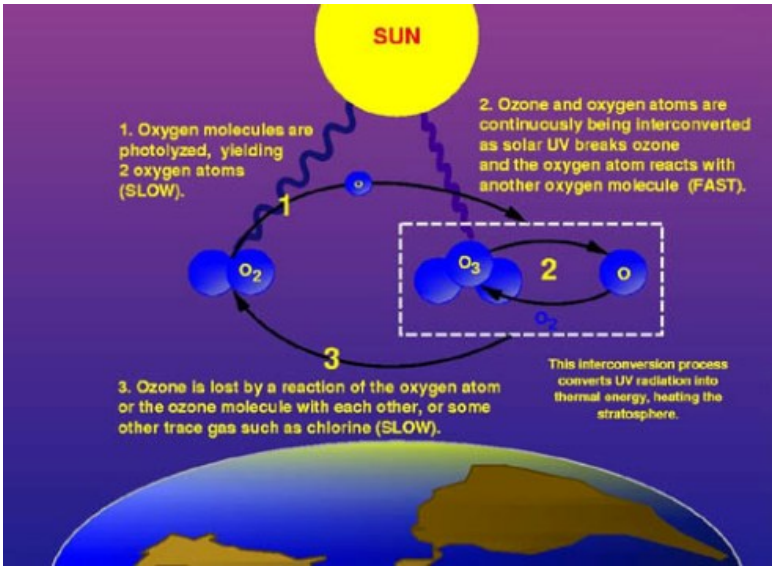

Figure 18.45: The ozone cycle involves the conversion of oxygen molecules to ozone (1 and 2) a slower reconversion of ozone molecules to oxygen (3). Interactions among ozone molecules or the presence of other reactive gases trigger the loss of ozone.

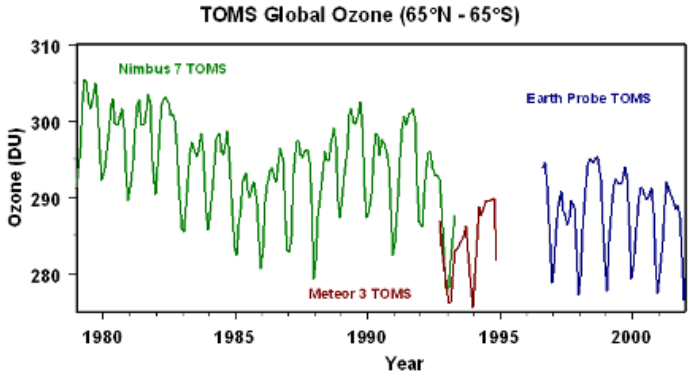

Figure 18.46: Total global monthly ozone levels measured by three successive spectrometers (TOMS) show both seasonal variations and a general decline.

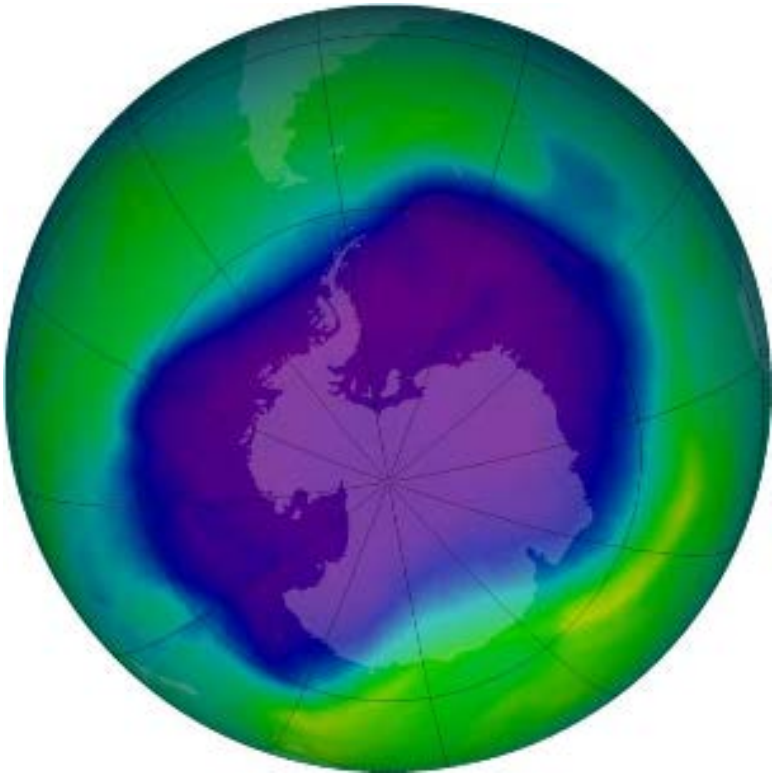

Figure 18.47: On September 24, 2006 the seasonal ozone hole over the Antarctic covered a record daily area (29.5 million square kilometres or 11.4 million square miles). Blue and purple areas show the lowest ozone levels, and green, yellow, and red indicate successively higher levels.

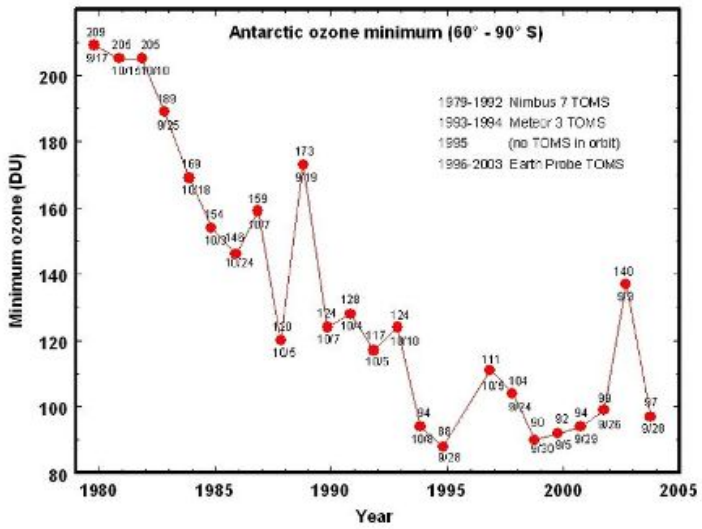

Figure 18.48: Lowest annual values of ozone in the ozone hole decreased dramatically between 1980 and 1995. Before 1980, values less than 200 Dobson units were rare, but in recent years, values near 100 units are common. Unusually high temperatures in the Antarctic stratosphere may have caused the high reading in 2002.

toward the breakdown of ozone. Chlorine and bromine gases have increased due to the use of *chlorfluorocarbons* (CFCs) for aerosol sprays, refrigerants (Freon), cleaning solvents, and fire extinguishers. These ozone-depleting substances (ODS) escape into the stratosphere, and when UV radiation frees chlorine and bromine atoms, these unstable atoms break down ozone. Scientists estimate that CFCs take 15 years to reach the stratosphere, and can remain active for 100 years. Each chlorine atom can catalyze thousands of ozone breakdown reactions.

Ozone depletion and the resulting increase in levels of UV radiation reaching earth could have some or all of the following consequences:

- effects on human health
- increase in skin cancers, including melanomas
- increased incidence of cataracts
- decreased levels of vitamin A
- possible increase in levels of vitamin D produced by the skin
- reduced abundance of UV-sensitive nitrogen-fixing bacteria
- loss of crops dependent on these bacteria
- disruption of nitrogen cycles
- loss of plankton (supported by a supernova-related extinction event 2 million years ago)

- disruption of ocean food chains

Most of these effects are based on the ability of UV radiation to alter DNA sequences. It is this potential which has made the Ozone Layer such a gift to life ever since photosynthesis provided the oxygen to fuel its production. Its total loss would undoubtedly be devastating to nearly all life.

In 1987, 43 nations agreed in the Montreal Protocol to freeze and gradually reduce production and use of CFCs. In 1990, the protocol was strengthened to seek elimination of CFCs for all but a few essential uses. Today, Hydrochlorofluorocarbons (HCFCs – similar compounds which replace one chlorine with a hydrogen) have replaced CFCs, with only 10% of their ozone-depleting activity levels. Unfortunately, HCFCs are greenhouse gases (see next lesson), so their role as alternatives is a mixed blessing. HFCs (hydrofluorocarbons) are another substitute; because these contain no chlorine, they have no ozone-depleting activity, and their **greenhouse effect** is less than HCFCs (though still significant). One HFC is currently used in automobile air conditioners in the U.S.

If ozone-depleting substances have been virtually eliminated, is ozone depletion no longer a problem?

Unfortunately, we have not yet reached that point. Levels of CFCs in the atmosphere are beginning to decline, and ozone levels appear to be stabilizing (**Figures** 18.47 and 14) for years after 2000). Scientists predict that ozone levels could recover by the second half of this century; the delay is due to the long half-life of CFCs in the stratosphere. However, recovery could be limited or delayed by two unknowns:

1. Developing countries outside the Montreal Protocol could increase their use of CFCs.
2. According to scientists, global warming would cool the stratosphere and increase ozone depletion because cooler temperatures favor ozone decomposition.

Preventing Air Pollution

Throughout this lesson, we have discussed solutions to specific problems for our atmosphere. A quick recap of ways to maintain our atmosphere and its ecosystem services from this chapter includes:

- Reducing use of fossil fuels
- Switching to cleaner fuels, such as nuclear power
- Switching to renewable energy sources
- Increasing fuel efficiencies
- Supporting legislation for fuel efficiencies
- Supporting national and international agreements to limit emissions

- Utilizing pollution control technologies: e.g., scrubbers on smokestacks and catalytic converters for motor vehicles
- Creating and supporting urban planning strategies

As always, costs are high and tradeoffs must be considered. The classic example is nuclear power, whose effects on the atmosphere are less than those of fossil fuels. Unfortunately, it has high potential for health damage and high costs – both economic and environmental – for storage and transport of nuclear waste.

Because fossil fuel use is the cause of so many atmospheric as well as water and soil pollutants, the solutions mentioned in the last two lessons apply here, as well. The final lesson on Climate Change relates directly to both fossil fuel combustion and atmospheric change, so more pollution solutions, specific to climate change, will be presented. You should also review the individual responses at the end of the lesson on **biodiversity**, because that list focuses on ways you can change your own life to help protect the environment.

Lesson Summary

- Earth's atmosphere, as we understand it today, provides ideal conditions and essential raw materials for life.
- Throughout Earth's history, the atmosphere has changed dramatically, and life caused some of the changes.
- Within human history, the atmosphere had been in a dynamic equilibrium: balancing photosynthesis, respiration, evaporation, and precipitation.
- Primary pollutants are directly added to the atmosphere by processes such as fires or combustion of fossil fuels. Secondary pollutants are formed when primary pollutants interact with sunlight, air, or each other.
- The majority of air pollutants can be traced to the burning of fossil fuels for heat, electricity, industry, transportation, and waste disposal.
- Worldwide, air pollution causes as many as 2.4 million deaths each year.
- Aerosols (particulates and liquid droplets) cab cause global dimming, or reduction in sunlight reaching the Earth.
- Light pollution can interfere with bird migrations, sea turtle reproduction, nocturnal animal behavior, and human activity.
- Rain, snow, fog, dew, and even dry particles which have an unusually low pH are commonly considered together as Acid Rain.
- Normal rain has a pH of about 5, due in part to formation of a weak (carbonic) acid from CO_2.
- Burning fossil fuels adds NO_x and SO_x gases to the atmosphere; these form strong acids (nitric and sulfuric) and change the pH of rain to as low as 2.4.
- Acid rain leaches nutrients and toxins from soils, weakening forests and killing aquatic animals.

- Limestone in bedrock or watersheds buffers the effects of acid rain for certain lakes.
- The development of taller smokestacks only sent pollution elsewhere, but scrubbers in smokestacks and catalytic converters in motor vehicles help to reduce emissions.
- The Ozone Layer in the stratosphere – formed from O_2 – protects Earth's life from mutagenic UV radiation.
- Ground-level ozone – formed from automobile exhaust and industry – is a component of smog, which irritates eyes and respiratory membranes.
- Ozone depletion is a global reduction in the thickness of the ozone layer, caused by chlorine and bromine atoms which reach the stratosphere.
- The ozone hole is a seasonal thinning of ozone above the Antarctic.
- CFCs in aerosol sprays, refrigerants (Freon), cleaning solvents, and fire extinguishers are the primary ozone-depleting substances (ODSs).
- The 1987 Montreal Protocol has reduced the use of CFCs and ozone depletion.
- Chemical substitutes, though less harmful, still cause damage, and countries outside the Protocol may still add ODS to the atmosphere.
- Global warming would cool the stratosphere and increase ozone depletion, because cooler temperatures favor ozone decomposition.
- Because fossil fuels are the source of many air pollutants, reducing their use is the key to solving air pollution problems.
- Technology can help by developing alternative energy sources, increasing fuel efficiencies, and improving pollution control.
- Governments can help by legislating fuel efficiencies and pollution control, urban planning, and forging agreements with other governments.

Review Questions

1. Summarize the importance of the gaseous "life support system" which Earth's atmosphere provides, and the dynamic equilibrium which characterizes the natural atmosphere.
2. Describe the ecosystem services provided by Earth's atmosphere.
3. Distinguish between primary and secondary pollutants, and give an example of each.
4. Define acid rain and trace the steps in its formation.
5. Why is rain with a pH of 5 not considered acid rain?
6. Analyze the effects of acid rain on soils, water resources, vegetation, animals, and humans.
7. Define ozone depletion and explain its causes.
8. Explain the consequences of ozone depletion.
9. Chart the air pollution problems discussed in this chapter together with a primary cause and an important prevention practice for each.

Table 18.7:

Problem	Major Cause	Major Prevention Practice
Global Dimming	Dust from erosion	Contour plowing, conservation tillage, cover crops
Light Pollution	Urbanization, artificial lights	Alteration of spectra and design of lights
Smog	Automobile exhaust	Catalytic converters, emissions control
Acid Rain	Generation of electricity from coal	Reduce use, scrubbers
Ozone Depletion	CFC emission	Eliminate use, find substitutes

10.
11. Why are international treaties, such as the Montreal Protocol and the Kyoto Treaty, so important in solving air pollution problems?

Further Reading / Supplemental Links

- US Environmental Protection Agency, *Effects of Acid Rain - Surface Waters and Aquatic Animals,* ACID RAIN, US EPA website, last updated 8 June 2007. Available online at:
- http://www.epa.gov/acidrain/effects/surface_water.html
- http://www.epa.gov/highschool/air.htm
- http://www.anr.state.vt.us/site/html/reflect/April5.htm
- http://www.epa.gov/acidrain/
- http://www.atm.ch.cam.ac.uk/tour/
- http://www.epa.gov/ozone/
- http://www.pbs.org/wgbh/nova/sun/
- http://www.documentary-film.net/search/sample.php
- http://www.skyandtelescope.com/resources/darksky
- http://www.wellesley.edu/Biology/Faculty/Mmoore/Content/Moore_2000.pdf
- http://en.wikipedia.org

Vocabulary

acid rain Precipitation in any form which has an unusually low pH.

aerosols Airborne solid particles or liquid droplets.

air pollution Alteration of the Earth's atmosphere by chemical, particulate, or biological materials.

algal bloom A rapid increase in the growth of algae, often due to a similar increase in nutrients.

anthropogenic sources Sources of pollution related to human activities.

biodiversity Variation in life – at all levels of organization: genes, species, and ecosystems.

ecosystem A functional unit comprised of living things interacting with their nonliving environment.

eutrophication An increase in nutrient levels in a body of water, often followed by an increase in plant or algae production.

global dimming A reduction in the amount of radiation reaching the Earth's surface.

global warming The recent increase in the Earth's average near-surface and ocean temperatures.

greenhouse effect The trapping by the atmosphere of heat energy radiated from the Earth's surface.

light pollution Production of light by humans in amounts which are annoying, wasteful, or harmful.

nonpoint source pollution Runoff of nutrients, toxins, or wastes from agricultural, mining, construction, or developed lands.

ozone depletion Reduction in the stratospheric concentration of ozone molecules, which shield life from damaging ultraviolet radiation.

ozone hole A seasonal reduction in ozone levels over Antarctica.

ozone layer A concentration of ozone molecules located between 15 and 35 kilometers above Earth's surface in the stratosphere.

point source pollution Single site sources of nutrients, toxins, or waste, such as industrial or municipal effluent or sewer overflow.

pollution Release into the environment of chemicals, noise, heat or even light beyond the capacity of the environment to absorb them without harmful effects on life.

primary pollutants Substances released directly into the air by processes such as fire or combustion of fossil fuel.

secondary pollutants Substances formed when primary pollutants interact with sunlight, air, or each other.

sustainable use Use of resources at a rate which meets the needs of the present without impairing the ability of future generations to meet their needs.

Points to Consider

- What are the major ecosystem services provided by our atmosphere?
- Could you now explain to a friend or family member the difference between the "hole in the ozone" and "global warming"?
- In what ways have we already begun to add the costs of atmospheric changes to our economic system?
- Can you think of additional ways in which we could build in these costs?
- How can we gain support for adding environmental costs to economic costs?

18.4 Lesson 18.4: Climate Change

Lesson Objectives

- Explain the mechanism of the greenhouse effect.
- Recognize that the greenhouse effect maintains an equilibrium.
- Compare greenhouse conditions on Earth to those on Mars and Venus.
- Explain the extent of current increases in the Earth's temperature.
- Review past changes in the Earth's temperatures.
- Summarize the evidence and support for greenhouse gases as the cause of recent global warming.
- Discuss the significance of global warming for Earth's ecosystems.
- Relate global warming to current global stability.
- List the atmospheric gases that absorb the Earth's thermal radiation, and their sources.
- Evaluate possible solutions to the problem of global climate change.
- Recognize the tradeoffs required by nuclear power plants: reduced emissions vs. radioactive fuels and waste

Introduction

On December 10, 2007, the Intergovernmental Panel on Climate Change (IPCC) and former US Vice President Al Gore received the Nobel Peace Prize "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change." The Peace Prize is designated "to the person who shall have done the most or the best work for *fraternity between the nations, for the abolition or reduction of standing armies and for the holding and promotion of peace congresses*." A high honor, the award also announced to the world that climate change (**Figure** 18.49) is a critical issues for the future of the Earth and its people. What is climate change? What are its causes? How do its effects relate to world peace? What are "the foundations for the measures that are needed to counteract such change"? Can individuals like us help? These are the questions we will explore in this last lesson about human ecology.

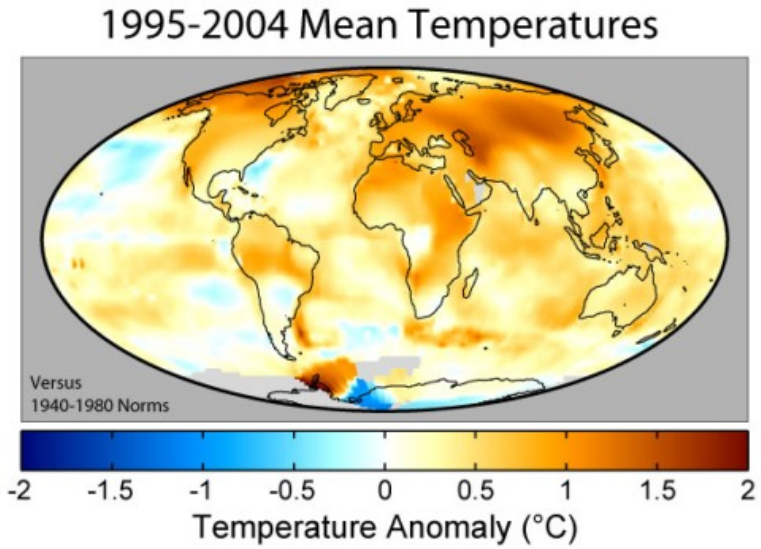

Figure 18.49: Temperature variations from 1940-1980 averages show that most of the Earth warmed significantly in just a single decade. The average temperature change across the entire globe for this period is 0.42C (0.76 F). Over the past 100 years, surface air temperatures have risen 0.74 ± 0.18 °C (1.33 ± 0.32 °F).

What is the Greenhouse Effect?

The Greenhouse Effect is a natural feature of Earth's atmosphere – yet another ecosystem service. Without the Greenhouse Effect, Earth's surface temperature would average -18°C (0°F) – a temperature far too cold to support life as we know it. With the Greenhouse Effect, Earth's surface temperature averages 15°C (59°F), and it is this temperature range to which today's diversity of life has adapted.

How does this ecosystem service work? The Greenhouse Effect is summarized in **Figure** 18.50. Of the solar radiation which reaches the Earth's surface, as much as 30% is reflected back into space. About 70% is absorbed as heat, warming the land, waters, and atmosphere (you may recall that only about 1% is converted to chemical energy by photosynthesis). If there were no atmosphere, most of the heat would radiate back out into space as infrared radiation. Earth's atmosphere, however, contains molecules of water (H_2O), carbon dioxide (CO_2), methane (CH_4), and ozone (O_3), which absorb some of the infrared radiation. Some of this absorbed radiation further warms the atmosphere, and some is emitted, radiating back down to the Earth's surface or out into space. A balance between the heat which is absorbed and the heat which is radiated out into space results in an equilibrium which maintains a constant average temperature for the Earth and its life.

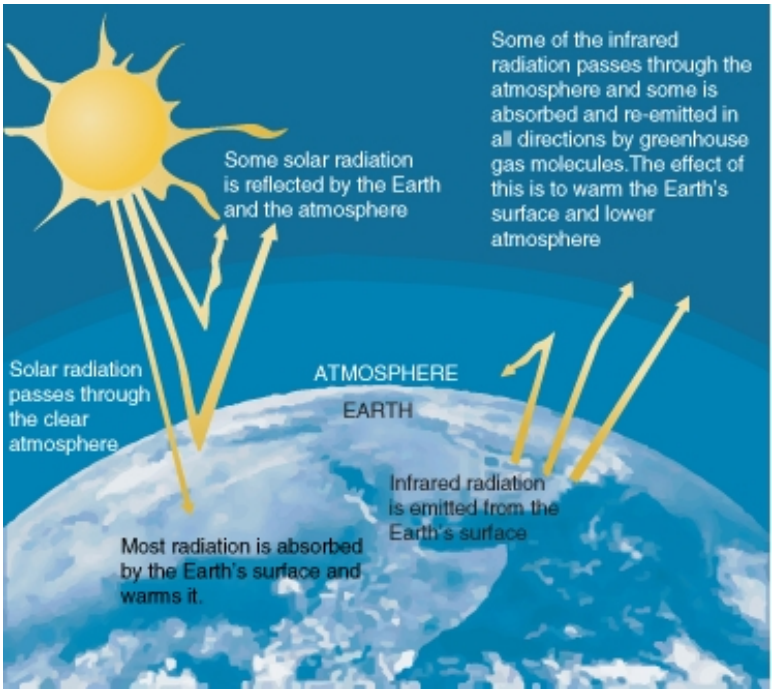

Figure 18.50: Without greenhouse gases, most of the sun's energy (transformed to heat) would be radiated back out into space. Greenhouse gases in the atmosphere absorb and reflect back to the surface much of the heat which would otherwise be radiated.

If we compare Earth's atmosphere to the atmospheres which surround Mars and Venus (**Figure** 18.51), we can better understand the precision and value of Earth's thermal equilibrium. Mars' atmosphere is very thin, exerting less than 1% of the surface pressure of our own. As you might expect, the thin atmosphere cannot hold heat from the sun, and the average surface temperature is -55°C (-67°F) – even though that atmosphere is 95% CO_2 and contains a great deal of dust. Daily variations in temperature are extreme, because the atmosphere cannot hold heat.

In contrast, Venus' atmosphere is much thicker than Earth's, exerting 92 times the surface

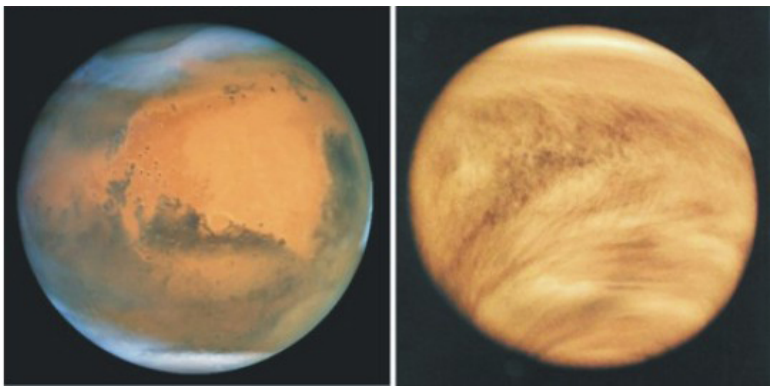

Figure 18.51: The thickness of a planet's atmosphere strongly influences its temperature through the Greenhouse Effect. Mars (left) has an extremely thin atmosphere, and an average temperature near -55C. Venus (right) has a far more dense atmosphere than Earth, and surface temperatures reach 500C.

pressure of our own. Moreover, 96% of the atmosphere is CO_2, so a strong Greenhouse Effect heats the surface temperature of Venus as high as 500°C, hottest of any planet in our solar system. The thick atmosphere prevents heat from escaping at night, so daily variations are minimal. Venus' atmosphere has many layers which vary in composition, and scientists have identified a layer about 50 km from the surface which could harbor liquid water and perhaps even life; some scientists propose that this would be a reasonable location for a space station. Near this altitude, pressure is similar to the Earth's sea level pressure, and temperatures range from 20°C to 37°C. Nitrogen, though only 3.5% of Venus' atmosphere, is present in the same overall amounts as on Earth (because the density on Venus is so much greater); oxygen, however, is absent, and sulfuric acid would present challenges.

Considering the extremes of Greenhouse Effects on Mars and Venus, we can better appreciate the precise balance which allows our own atmosphere to provide temperatures hospitable to liquid water and life. Inevitably, we must also ask this chapter's repeating query: how have human activities affected this equilibrium? This leads us back to the 2007 Nobel Peace Prize, and an evolving consensus that our species is responsible for significant global warming.

Global Warming

Global warming refers to the recent increase in the Earth's average near-surface and ocean temperatures (**Figure** 18.52). During the past 100 years, surface air temperatures have risen 0.74 ± 0.18 °C (1.33 ± 0.32 °F). Multiple sources agree that the two warmest years since the introduction of reliable instrumentation in the 1800s were 1998 and 2005.

This recent increase contrasts with relatively stable temperatures shown by scientific data for the previous two millennia. Multiple sets of temperature data inferred from tree rings, coral growth, and ice core samples are compiled in **Figure** 18.53. Warmly debated exceptions to

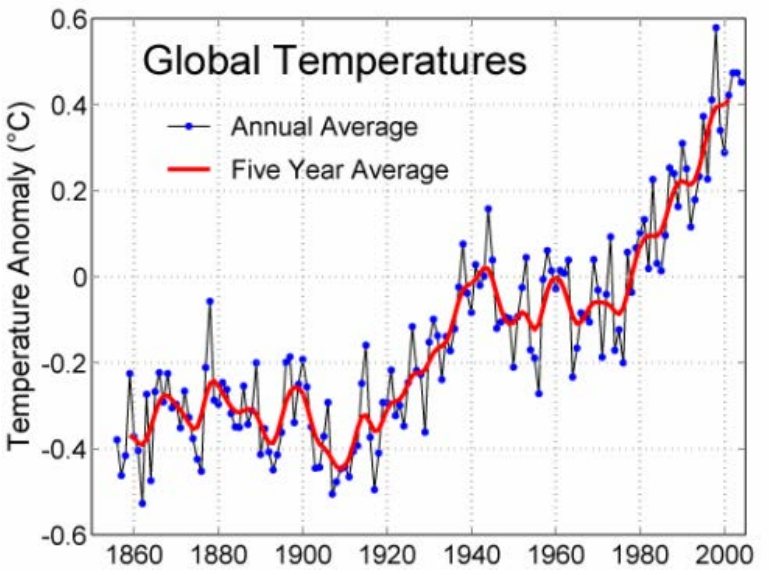

Figure 18.52: Global warming refers to the increase in Earth's average near-surface temperatures over the past 100 years. "Anomalies" measure deviation from 1961-1990 averages.

the stability include a warm period during the Middle Ages and a "Little Ice Age," attributed to decreased solar activity and increased volcanism.

According to paleoclimatologists, on a scale of millions of years Earth's temperatures have varied almost regularly (over time intervals of roughly 140 million years) from those which support global tropics to continental glaciations (**Figure** 18.54). Scientists estimate the global average temperature difference between an entirely glaciated Earth and an ice-free Earth to be 10°C.

The causes of Ice Ages are not completely understood, but greenhouse gases, especially CO_2 levels, often correlate with temperature changes (**Figure** 18.55). Rapid buildup of greenhouse gases in the Jurassic Period 180 million years ago correlates with a rise in temperature of 5°C (9°F). Similar changes have been hypothesized as causes for the dramatic Permian Extinction 250 million years ago and the Paleocene-Eocene Thermal Maximum (one of the most rapid and extreme global warming events recorded in geologic history) 55 million years ago. Paleoclimatologist William Ruddiman proposes that human activities began to affect global CO_2 levels as long ago as 8,000 years, when agriculture and deforestation began. Ruddiman argues that without this early contribution to greenhouse gases, cycles indicate the Earth would already have entered another Ice Age.

Others dispute Ruddiman's "overdue-glaciation" theory, but most scientists today agree that recent global warming since 1850 is caused by an unprecedented rise in atmospheric CO_2 (**Figure** 18.56) which resulted from human activities – primarily burning of fossil fuels, but also continuing deforestation and changes in land use. Fossil fuels burn organic compounds in the same way your cells burn glucose to make ATP: a product of both reactions

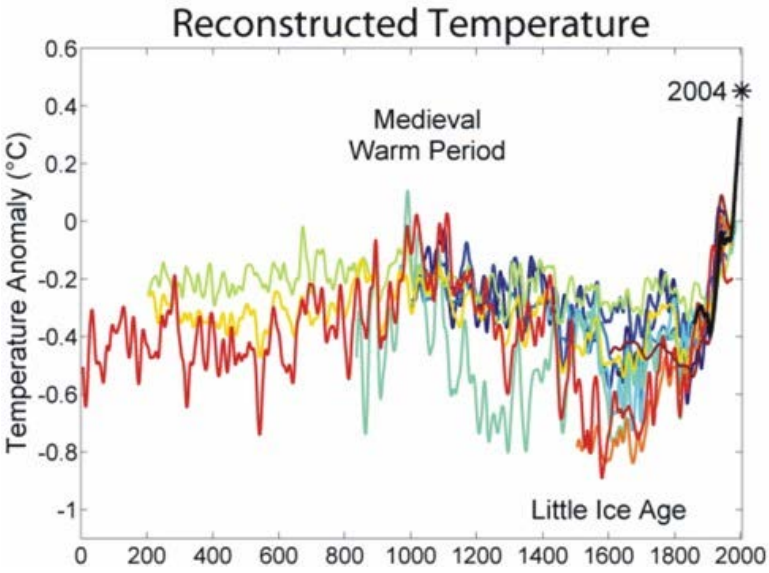

Figure 18.53: Global temperatures compiled from tree ring, coral growth, ice core analysis, and historical records, show relative stability over the last 2,000 years before about 1850, interrupted by a debatable Medieval warming and a more recent cooling termed the "Little Ice Age." Colored lines indicate different published data sources. For more detail on the increase since 1850, refer to Figure 3.

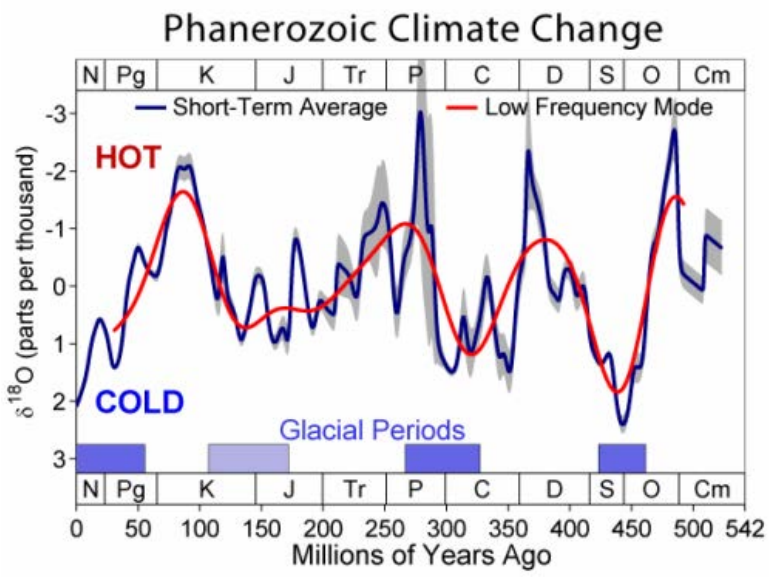

Figure 18.54: Paleoclimatological measures of global temperatures show dramatic fluctuations in temperature. Graphs should be read from right (past) to left (present). Ice core data for temperature is recorded in oxygen isotope units rather than C.

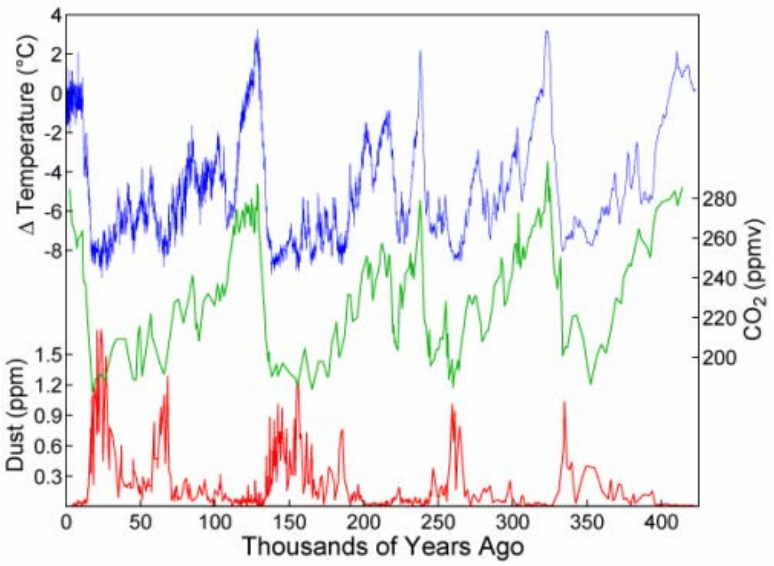

Figure 18.55: Over the past 450,000 years, temperature changes (blue) correlate closely with changes in atmospheric CO (green) and dust levels (red).

is CO_2. Deforestation and other land use changes contributes to the CO_2 levels from the opposite direction – a decrease in photosynthesis, which would have removed CO_2 from the atmosphere. Slash-and-burn destruction of tropical forests combines the worst of both worlds; burning adds CO_2 to the atmosphere, and the loss of layers of vegetation decreases CO_2 use.

Two additional greenhouse gases having anthropogenic (human activity) sources are methane (CH_4) and nitrous oxide (NO). Agriculture adds both of these to the atmosphere; cattle production is responsible for much of the methane, a powerful greenhouse gas. Land use changes, waste processing, and fossil fuel production, which we've already implicated in CO_2 increases, are other **anthropogenic** (human-caused) sources. A last but important contributing factor is secondary to these primary causes; triggers of "runaway greenhouse effects" will be discussed below.

Although the causal connections between fossil fuel combustion, deforestation, greenhouse gases, the greenhouse effect, and global warming have been strongly debated in the past, the majority of the world's scientific organizations now support these relationships, and many use the term "consensus." (See "Scientific Opinion about Climate Change" in Further Reading.) The awarding of the Nobel Peace Prize to the organization which focuses most directly on climate change, the IPCC, highlights this consensus. Alternative hypotheses include variation in solar activity; several references are included in Further Reading. The IPCC projects future temperature increases ranging from 1.1 °C to 6.4 °C (2.0 °F to 11.5 °F) between 1990 and 2100. Predictions from multiple models which incorporate connections between greenhouse emissions and global warming are summarized in **Figure** 18.57; all show

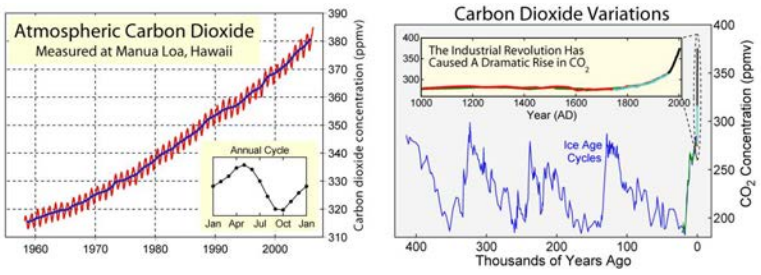

Figure 18.56: Since the Industrial Revolution began, the burning of fossil fuels has dramatically increased atmospheric concentrations of CO to levels unprecedented in the last 400 thousand years. The graph on the right integrates recent measurements with paleoclimatologic data.

significant rises in temperature by 2100.

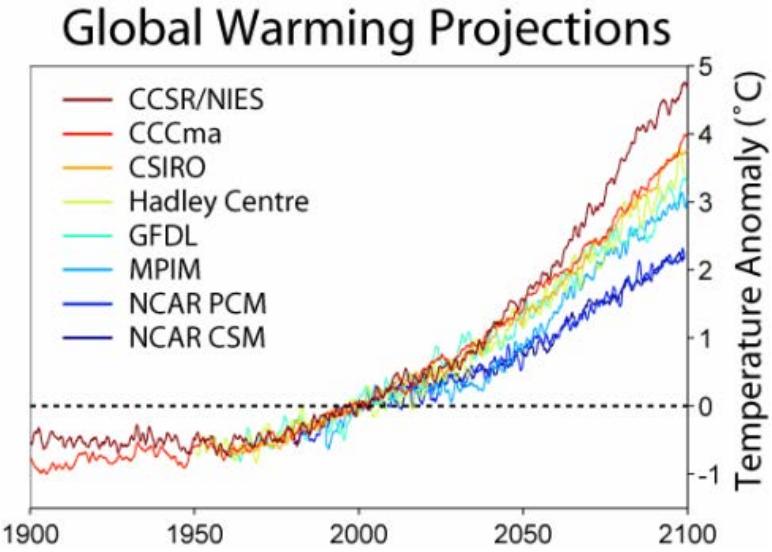

Figure 18.57: Various models of climate change which include "business-as-usual" increases in greenhouse gas emissions predict continuing increases in global temperature; this graph compares the projected increases to temperatures during the year 2000.

Once again, then, we "have met the enemy" and "he is us." What have we done? What are the environmental and socioeconomic consequences of this human disruption in atmospheric equilibrium?

A partial list of effects of climate change includes:

Direct Physical Effects

- Melting of glaciers and a consequent rise in sea level, already documented (**Figure** 18.58)
- Sea level rise of 18-59 cm predicted by 2100
- River flooding followed by drought
- Coastal flooding and shoreline erosion

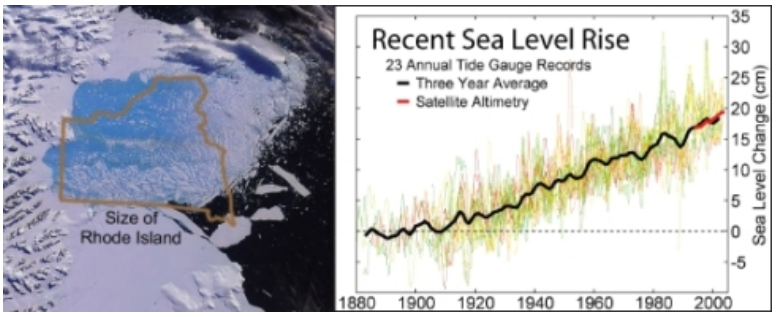

Figure 18.58: Glacial melting (left) and a rise in sea level (right) are two consequences of global warming. The left image shows the Larsen Ice Shelf B, which broke up during February of 2002 after bordering Antarctica for as long as 12,000 years. Excluding polar ice caps, 50% of glacial areas have disappeared since the turn of the century. Although sea levels have risen since the end of the last Ice Age, rates increased by a factor of 10 beginning about 1900.

- Melting permafrost, leading to release of bog methane (CH_4) increasing warming via positive feedback*
- Changing patterns of precipitation
- Regional drought
- Regional flooding
- Ocean warming, leading to increased evaporation
- Increasing rainfall
- Increasing erosion, deforestation, and desertification
- Release of sedimentary deposits of methane (CH_4) hydrates – positive feedback*
- Ocean acidification: 0.1 pH unit drop already documented; 0.5 more predicted by 2100
- Loss of corals
- Loss of plankton and fish
- Temperature extremes
- Increasing severity of storms such as tropical cyclones, already documented (**Figure** 18.59)
- Further reductions in the Ozone Layer (due to cooling of the stratosphere)

Figure 18.59: The proportion of hurricanes reaching category 4 or 5 increased from 20% in the 1970s to 35% in the 1990s. The EPA and the World Meteorological Organization connect this increase to global warming, and NOAA scientists predict a continuing increase in frequency of category 5 storms as greenhouse gases rise.

Ecosystem Effects

- Contributions to the Sixth Extinction reaching as much as 35% of existing plant and animal species
- Decline in cold-adapted species such as polar bears and trout
- Increase in forest pests and fires
- Change in seasonal species, already documented
- Potential increase in photosynthesis, and consequent changes in plant species
- Loss of carbon to the atmosphere due to
- Increasing fires, which together with deforestation lead to positive feedback
- Increasing decomposition of organic matter in soils and litter

Socioeconomic Threats Result From Some of the Above Changes

These include:

- Crop losses due to climate and pest changes and desertification
- Increasing ranges for disease vectors (e.g., mosquitoes – malaria and dengue fever)
- Losses of buildings and development in coastal areas due to flooding
- Interactions between drought, desertification, and overpopulation leading to increasing conflicts (**Figure** 18.60)

Figure 18.60: A camp in Sudan houses refugees from the far western province of Darfur, who fled from genocide intensified by severe drought. The Darfur conflict echoes predictions that global warming may increase drought and desertification in overpopulated regions and result in more such tragedies.

- Costs to the insurance industry as weather-related disasters increase
- Increased costs of maintaining transportation infrastructure
- Interference with economic development in poorer nations
- Water scarcity, including pollution of groundwater
- Heat-related health problems

Threats to Political Stability

- Migrations due to poverty, starvation, and coastal flooding
- Competition for resources

Note that at least three(*) of the direct physical effects – melting permafrost, ocean warming, and forest fires/deforestation - can potentially accelerate global warming, because temperature increases result in release of more greenhouse gases, which increase temperatures, which result in more greenhouse gases – a positive feedback system aptly termed a "**runaway greenhouse effect**." Here's how it could work: rising temperatures are warming the oceans and thawing permafrost. Both oceans and permafrost currently trap huge quantities of methane – beneath sediments and surface – which would undergo massive releases if temperatures reach a critical point. Recall that methane is one of the most powerful greenhouse gases, so the next step would be further increase in temperatures. Warmer oceans and more

thawed permafrost would release more quantities of methane – and so on. These compounding effects are perhaps the most convincing arguments to take action to reduce greenhouse gas emission and global warming.

What measures have been considered?

Preventing Climate Change

Basically, greenhouse gases are products of fossil fuel combustion; according to the EPA, more than 90% of U.S. greenhouse gas emissions come from burning oil, coal, and natural gas. Therefore, energy use is the primary target for attempts to reduce future global warming. In **Figure** 18.61 you can see the sources of emission for three major greenhouse gases in 2000, when CO_2 was 72% of the total, CH_4 18%, and NO 9%. Chlorofluorocarbons (CFCs, HCFCs, and HFCs) are also greenhouse gases; refer to the lesson on The Atmosphere for more information about them.

Knowing the causes of climate change allows us to develop potential solutions. Direct causes include combustion of fossil fuels, deforestation and other land use changes, cattle production, agriculture, and use of chlorofluorocarbons. Runaway effects can result from temperature-dependent release of methane from permafrost and ocean sediments, and forest fires or intentional burning. Unfortunately, the best way to avoid runaway effects is to prevent temperature increases. Prevention, then, should address as many of these causes as possible. A partial list of solutions being considered and adopted follows.

1. Reduce energy use.
2. Switch to cleaner "alternative" energy sources, such as hydrogen, solar, wind, geothermal, waste methane, and/or biomass.
3. Increase fuel efficiencies of vehicles, buildings, power plants, and more.
4. Increase **carbon (CO_2) sinks**, which absorb CO_2 - e.g., by planting forests.
5. **Cap emissions** release, through national and/or international legislation, alone or in combination with carbon offset options (see below).
6. Sell or trade **carbon offsets or carbon credits**. Credits or offsets exchange reductions in CO_2 or greenhouse emissions (tree-planting, investment in alternative energy sources, methane capture technologies) for rights to increase CO_2 (personally, as for air travel, or industry-wide).
7. Key urban planning to energy use, e.g., efficient public transportation.
8. Develop **planetary engineering**: radical changes in technology (such as building solar shades of dust, sulfates, or microballoons in the stratosphere), culture (population control), or the biosphere (e.g. iron-seeding of the oceans to produce more phytoplankton to absorb more CO_2).
9. Legislate Action: International agreements such as the 2005 Kyoto Protocol (which the US has not yet ratified), or national carbon taxes or caps on emissions. Interestingly, in the U.S., some States and groups of States are taking the lead here.

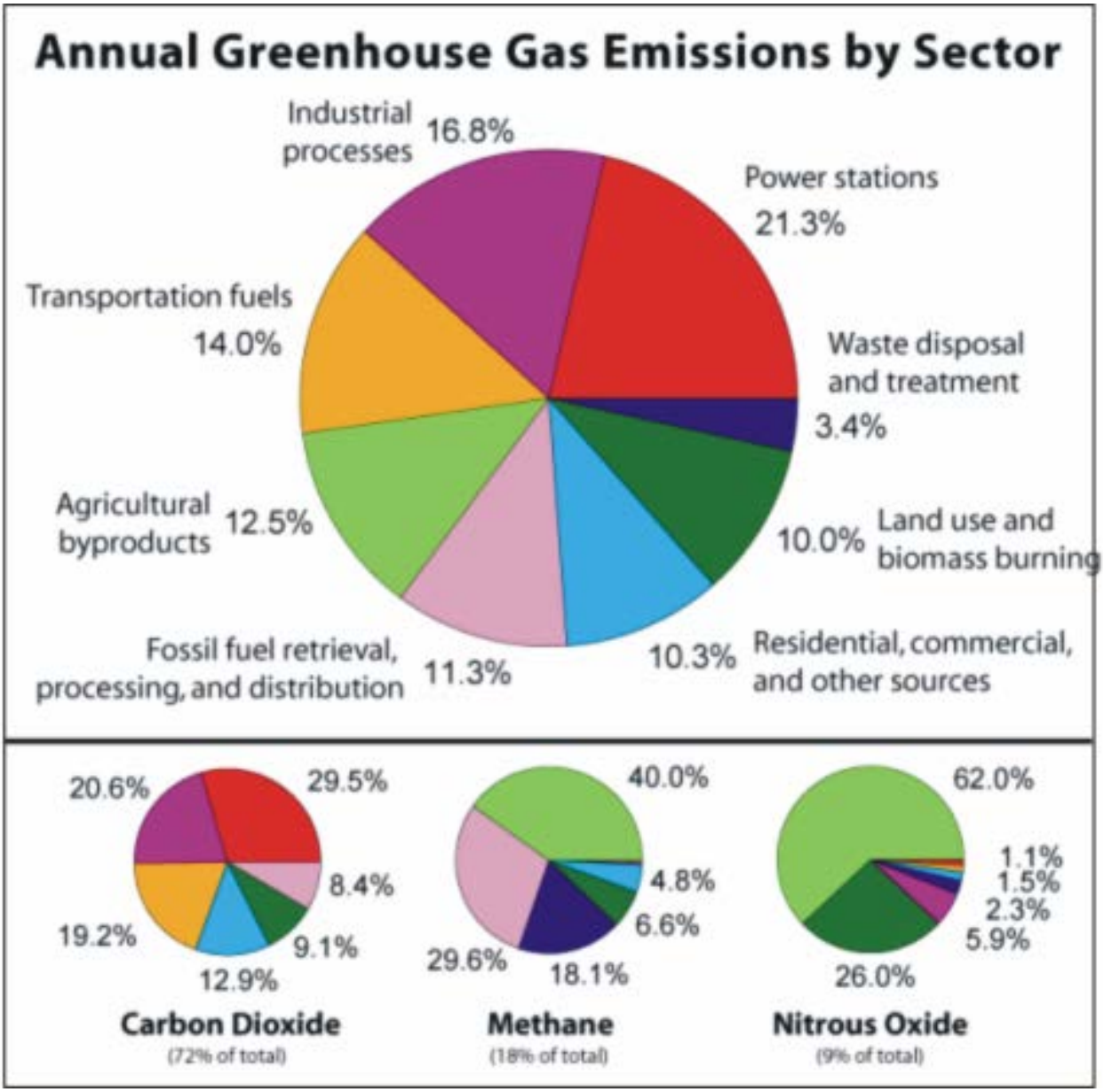

Figure 18.61: Global greenhouse emissions during 2002 show sources for each of the three major greenhouse gases. Knowing the causes makes finding solutions clear, but not necessarily easy!

10. Set goals of carbon neutrality: in 2007, the Vatican announced plans to become the first **carbon-neutral** state.
11. Support developing nations in their efforts to industrialize and increase standards of living without adding to greenhouse gas production.

Every potential solution has costs and benefits which must be carefully considered. Human health, cultural diversity, socioeconomics, and political impacts must be considered and kept in balance. For example, nuclear power involves fewer greenhouse gas emissions, but adds the new problems of longterm radioactive waste transport and storage, danger of radiation exposure to humans and the environment, centralization of power production, and limited supplies of "clean" uranium fuels. Studies of costs and benefits can result in solutions which make effective tradeoffs and therefore progress toward the goal of lowering greenhouse gases and minimizing future global warming.

We have reached the point where we understand how and the extent to which our activities have destabilized the Earth's atmosphere and reduced and threatened its ecosystem services. Now we need to move one step further, and put our knowledge to work in the form of action.

What will you do to help?

Lesson Summary

- The awarding of the 2007 Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) and former US Vice President Al Gore recognizes the potential impact of global warming on the economic, social, and political welfare of the world.

- The greenhouse effect is an ecosystem service which warms the Earth to temperatures which support life.
- The greenhouse effect involves water, carbon dioxide, methane, and ozone, which absorb heat that would otherwise be radiated out into space.
- Earth's atmosphere maintains an equilibrium between heat added by sunlight and heat lost by radiation.
- The atmosphere of Mars is too thin to hold heat, and that of Venus is so thick that temperatures reach 500°C.
- In 2000, the major greenhouse gases were CO_2, CH_4, and NO; CFCs and H_2O contribute, as well.
- Global warming refers to an increase in the Earth's temperature of 0.74°C (1.33°F) within the past 100 years.

- Paleoclimatologists document changes in the Earth's temperature over millions of years which cycle between tropical and ice age extremes – a variation of 10°C.
- Greenhouse gases, especially CO_2 levels, often correlate with temperature changes.

- Deforestation and agriculture – by reducing levels of CO_2 uptake – may have initiated warming 8,000 years ago.
- Most scientists today agree that fossil fuel combustion, deforestation, and agriculture contribute to greenhouse gases and the greenhouse effect.
- Global warming can cause physical changes for the Earth: melting of glaciers and permafrost, changes in precipitation patterns, temperature extremes, warming and acidification of the oceans, and ozone depletion.
- Melting of oceans and permafrost can release methane, resulting in a "runaway greenhouse effect."
- Ecological effects may include loss of biodiversity and addition of still more CO_2 to the atmosphere.
- Socioeconomic threats include crop losses, increased disease, water scarcity, and coastal flooding.
- Population growth and socioeconomic factors (especially interference with third world development) can combine to produce political instability and conflict.

- Most greenhouse gases are products of fossil fuel combustion, so reduced use, increased efficiency, and alternative fuel development are primary means of prevention of climate change.
- CO_2 uptake can be increased by eliminating deforestation, reforestation, and green roofs technology.
- Legislation from local to international levels can cap emissions and develop carbon offset trading.
- Careful urban planning can increase the efficiency of transportation and energy use.
- Planetary engineering could enact radical changes in technology, culture, or the biosphere.
- Support of third world efforts to develop without adding greenhouse gases could improve global stability.
- Every potential solution has costs and benefits which must be carefully considered; tradeoffs are necessary.

Review Questions

1. Explain the mechanism of the greenhouse effect.
2. Compare the effects of the greenhouse effect on Mars and Venus to that on Earth.
3. Define and quantify global warming.
4. Describe paleoclimatic changes over the course of Earth's history. How are these data collected, when no one was around to measure temperatures?
5. Summarize the evidence for greenhouse gases as the cause of recent global warming.
6. Discuss the significance of global warming for Earth's ecosystems.
7. Relate global warming to current global stability.

8. Connect the atmospheric gases that absorb the Earth's thermal radiation to their sources.
9. Combustion of fossil fuels is a common denominator for many problems related to Atmospheric and Water Resources. Clarify the connections for as many problems as you are able.
10. Distinguish between and describe the importance to global warming prevention of carbon sequestration, carbon sinks, carbon offsets, emission caps, emissions trading, and carbon neutrality.

Further Reading / Supplemental Links

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- http://www.eere.energy.gov/

Vocabulary

anthropogenic sources Sources of pollution related to human activities.

carbon (CO_2) sink A reservoir which increases absorption of CO_2 – e.g. a forest plantation.

carbon offsetting Mitigating or reducing greenhouse gas emissions, often as a trade-off from one location to another.

carbon sequestration Process which removes CO_2 from the atmosphere.

carbon-neutral Describes an individual, activity, industry, or a political unit which balances CO_2 release with activities which sequester carbon.

emissions cap Upper limit on CO_2 (or other pollutant) release; may be tradable or sellable.

emissions trading Reducing greenhouse emissions by purchasing or exchanging means of reducing CO_2 in exchange for rights to release CO_2 .

global warming The recent increase in the Earth's average near-surface and ocean temperatures.

greenhouse effect The trapping by the atmosphere of heat energy radiated from the Earth's surface.

greenhouse gas Atmospheric substance which transmits solar radiation but absorbs infrared radiation: CO_2, CH_4 and NO, for example.

planetary engineering Radical, often global changes in technology, culture, or the biosphere management.

runaway greenhouse effect A positive feedback loop in which increasing temperature triggers the release of more greenhouse gases, which further increase temperature, which releases more gases.

Points to Consider

- Do you think global warming is a good example of an "ecosystem service" – or perhaps a " biosphere service?" Explain your reasoning.
- How is the Greenhouse Effect both positive and negative?
- Which of the suggestions for preventing climate change do you think are most realistic for you?
- How might you, as an individual, contribute to national and international solutions to climate change?
- How might we do a better job of building the costs of global warming into the economics of fossil fuel use, deforestation, agriculture, and cattle production?

Image Sources

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Chapter 19

The Human Body

19.1 Lesson 19.1: Organization of the Human Body

Lesson Objectives

- Describe the levels of organization of the human body.
- Outline the role of a specialized cell.
- Identify the properties that make body cells and stem cells different from each other.
- List three types of stem cells.
- Identify the four tissue types found in the human body.
- Summarize how tissues and organs relate to each other.
- Name two body systems that work together for a common purpose.

Introduction

In most multicellular organisms, not all cells are alike. For example, the cells that make up your skin are different from cells that make up your liver, your blood, or your eyes. Yet, all these specialized cells develop from one single fertilized egg which means all of your cells have the same DNA. But liver, blood, and eye cells are very different from each other in form and function. While these cells are specialized for a specific job, there are other cells in the body that remain unspecialized. These cells multiply continuously to replace the millions of different body cells that die and need to be replaced every day.

Cells

Cells are the most basic units of life in your body. Each specialized cell has a specific function in the body. For example, nerve cells transmit electrical messages around the body,

and white blood cells patrol the body and attack invading bacteria. Other cells include specialized cells in the kidney (such as kidney glomerulus parietal cell), brain cells (such as astrocytes), stomach cells (such as parietal cells), and muscle cells (such as red and white skeletal muscle fibers). Cells group together in tissues to carry out a specific function, and different tissues work together to form organs. This grouping of cells and tissues is referred to as levels of organization. Complex multicellular organisms, which include flatworms and humans, have different levels of organization.

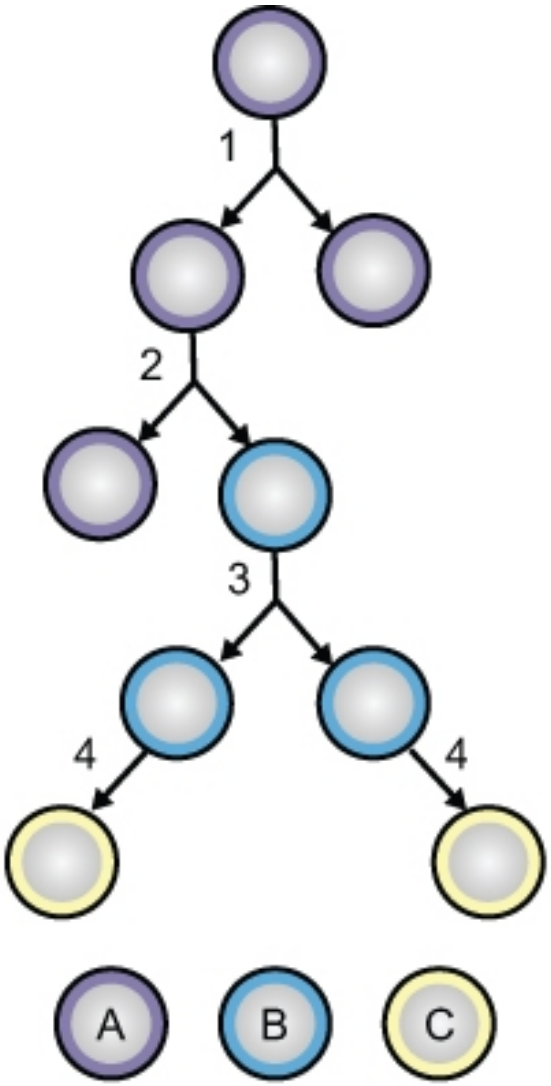
Differentiation

Every cell in the body originated from a single fertilized egg, which is called a zygote. The zygote divides many times to produce an embryo. These embryonic cells differentiate into many different cell types which in time give rise to all the cells types present in the body of all humans (and other mammals), from a new-born baby to an elderly adult. **Differentiation** is the process by which an unspecialized cell (such as a fertilized egg cell), divides many times to produce specialized cells that work together and make up the body. During differentiation, certain genes are turned on, or become activated, while other genes are switched off, or inactivated. This process is regulated by the cell. A differentiated cell will develop specific structures and perform certain functions.

A cell that is able to differentiate into all cell types within a body is called **totipotent**. They have "total potential" to differentiate into any cell type. In mammals, only the zygote and early embryonic cells are totipotent. A cell that is able to differentiate into many cell types, but not all, is called **pluripotent**. Such cells have "plural potential," (but not "total potential") to differentiate into most but not all cell types.

Stem Cells

An unspecialized cell that can divide many times and give rise to different, specialized cells is called a **stem cell**, as shown in **Figure** 19.1. Zygotes and embryonic cells are both types of stem cells. The stem cells found in embryos can divide indefinitely, can specialize into any cell type and are called **embryonic stem cells**. Embryonic stem cells are totipotent. Undifferentiated cells that are found within the body and that divide to replace dying cells and damaged tissues are called **adult stem cells**. Adult stem cells can divide indefinitely, and generate all the cell types of the organ from which they originate. They can potentially re-grow the entire organ from just a few cells. A third type of stem cell is found in blood from the umbilical cord of a new-born baby, and the placenta. These "cord blood stem cells" are considered to be adult stem cells because they cannot generate all body cell types, just different types of blood cells. Therefore, adult stem cells and cord blood stem cells are pluripotent.



A–Embryonic stem cells (purple)
B–adult stem cell (blue)
C–differentiated cell (yellow)
1–embryonic stem cell division to make more stem cells
2–totipotent embryonic stem cells can produce pluripotent adult stem cells
3–adult stem cells divide, and eventually differentiate into specialized cells. (4)

Figure 19.1: Division and differentiation of stem cells into specialized cells.

Stem Cells in Medicine

Stem cells are of great interest to researchers because of their ability to divide indefinitely, and to differentiate into many cell types. Stem cells have many existing or potential therapeutic applications. Such therapies include treatments for cancer, blood disorders, brain or spinal cord injuries, and blindness.

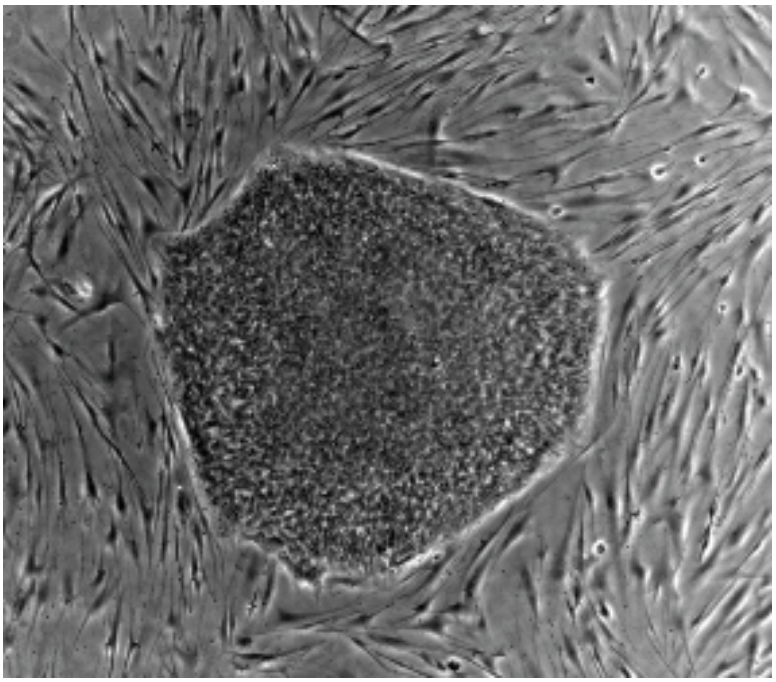


Figure 19.2: Human embryonic stem cell colony, which was grown in a laboratory on a feeder layer of mouse cells. Embryonic stem cells are totipotent. A video of human embryonic stem cell and their uses is available at An animation of stem cell procedures is available at

Embryonic stem cells, as shown in **Figure** 19.2, are taken from eggs that were fertilized in the laboratory and donated to research. They may have the greatest potential because they are totipotent, and thus have the most potential medical applications. However, embryonic stem cells harvested from a donated embryo differ from a potential patient's tissue type. Therefore, just as in organ transplantation, there is a risk of a patient's body rejecting transplanted embryonic stem cells. Some individuals and groups have objections to the harvesting of embryonic stem cells, because harvesting the stem cells involves the destruction of the embryo. Some researchers are looking into methods to extract embryonic stem cells without destroying the actual embryo. Other researchers have claimed success in harvesting embryonic stem cells from the embryonic fluid that surrounds a growing fetus.

Adult stem cells, including cord blood stem cells, have already been used to treat diseases of the blood such as sickle-cell anemia and certain types of cancer. Unlike embryonic stem cells, the use of adult stem cells in research and therapy is not controversial because the

production of adult stem cells does not require the destruction of an embryo. Adult stem cells can be isolated from a tissue sample, such as bone marrow, from a person. Scientists have recently discovered more sources of adult stem cells in the body. Adult stem cells have been found in body fat, the inside lining of the nose, and in the brain. Some researchers are investigating ways to revert adult stem cells back to a totipotent stage.

Tissues

A **tissue** is a group of connected cells that have a similar function within an organism. The simplest living multicellular organisms, sponges, are made of many specialized types of cells that work together for a common goal. Such cell types include digestive cells, tubular pore cells, and epidermal cells. Though the different cell types create a large organized, multicellular structure—the visible sponge—they are not organized into true tissues. If a sponge is broken up by passing it through a sieve, the sponge will reform on the other side.

More complex organisms such as jellyfish, coral, and sea anemones have a tissue level of organization. For example, jellyfish have tissues that have separate protective, digestive, and sensory functions. There are four basic types of tissue in the body of all animals, including the human body. These make up all the organs, structures and other contents of the body. **Figure** 19.3 shows an example of each tissue type.

The four basic types of tissue are:

- **Epithelial tissue** is made up of layers of tightly packed cells that line the surfaces of the body for protection, secretion, and absorption. Examples of epithelial tissue include the skin, the lining of the mouth and nose, and the lining of the digestive system.
- **Muscle tissue** is made up of cells contain contractile filaments that move past each other and change the size of the cell. There are three types of muscle tissue: smooth muscle which is found in the inner linings of organs; skeletal muscle, which is attached to bone and moves the body; and cardiac muscle which is found only in the heart.
- **Nervous tissue** is made up of the nerve cells (neurons) that together form the nervous system, including the brain and spinal cord.
- **Connective tissue** is made up of many different types of cells that are all involved in structure and support of the body. Bone, blood, fat, and cartilage are all connective tissues. Connective tissue can be densely packed together, as bone cells are, or loosely packed, as adipose tissue (fat cells) are.

Organs and Organ Systems

Organs are the next level of organization in the body. An **organ** is a structure made of two or more tissues that work together for a common purpose. Skin, the largest organ in the

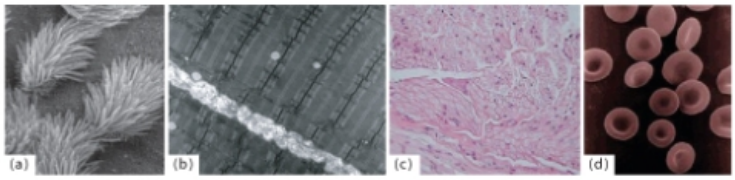


Figure 19.3: (a) Scanning electron micrograph (SEM) image of lung trachea epithelial tissue, (b) Transmission electron micrograph (TEM) image of skeletal muscle tissue, (c) Light microscope image of neurons of nervous tissue, (d) red blood cells, a connective tissue.

body, is shown in **Figure** 21.41. Organs can be as primitive as the brain of a flatworm (a group of nerve cells), as large as the stem of a sequoia (up to 90 meters in height (300 feet)), or as complex as a human liver. The human body has many different organs, such as the heart, the kidneys, the pancreas, and the skin. Two or all of the tissue types can be found in an organ. Organs inside the body are called internal organs. The internal organs collectively are often called viscera.

The most complex organisms have organ systems. An **organ system** is a group of organs that act together to carry out complex interrelated functions, with each organ focusing on a part of the task. An example of an organ system is the human digestive system in which the mouth and esophagus ingests food, the stomach crushes and liquefies it, the pancreas and gall bladder make and release digestive enzymes, and the intestines absorb nutrients into the blood. An organ can be part of more than one organ system. For example the ovaries produce hormones which make them a part of the endocrine system. The ovaries also make eggs which makes them part of the reproductive system. One of the most important functions of organ systems is to provide cells with oxygen and nutrients and removes toxic waste products such as carbon dioxide. A number of organ systems, including the cardiovascular and respiratory systems, work together to do this.

The different organ systems of the body are shown in **Table** 19.1. Sometimes the cardiovascular system and the lymphatic system are grouped together into one single system called the circulatory system.

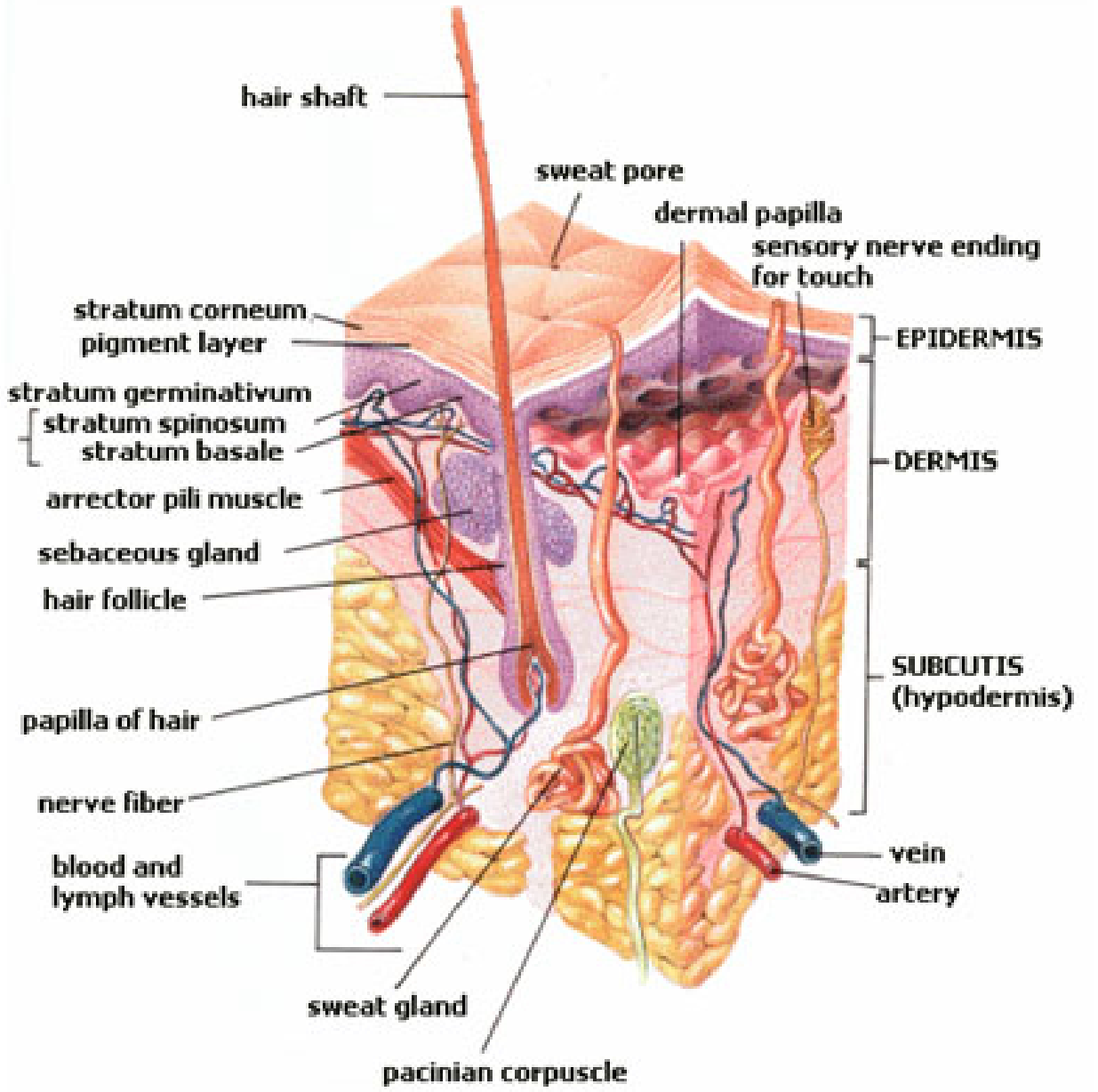


Figure 19.4: Your skin is the largest organ in your body. In this cross section image of skin, the four different tissue types (epithelial, connective, nervous, and muscle tissues) can be seen working together.

Table 19.1: **Major Organ Systems of the Human Body**

Organ System	Function	Organs, Tissues, and Structures Involved
Cardiovascular	Transporting oxygen, nutrients and other substances to the body cells, and wastes, carbon dioxide, and other substances away from cells; it can also help stabilize body temperature and pH	Heart, blood, blood vessels
Lymphatic	Defense against infection and disease, transfer of lymph between tissues and the blood stream	Lymph, lymph nodes, lymph vessels
Digestive	Processing of foods and absorption of nutrients, minerals, vitamins, and water	Salivary glands, esophagus, stomach, liver, gallbladder, pancreas, small intestine, large intestine
Endocrine	Communication within the body with hormones; directing long-term change over other organ systems to maintain homeostasis	Among many, the pituitary gland, pineal gland, thyroid, parathyroid gland, adrenal glands, testes, and ovaries
Integumentary	Protection from injury and fluid loss; physical defense against infection by microorganisms; temperature control	Skin, hair, and nails
Muscular	Movement, support, heat production	Skeletal, cardiac, and smooth muscles, tendons
Nervous	Collecting, transferring and processing information; directing short-term change over other organ systems in order to maintain homeostasis	Brain, spinal cord, nerves, and sense organs (eyes, ears, tongue, skin, nose)
Reproductive	Production of gametes (sex cells) and sex hormones; production of offspring	Fallopian tubes, uterus, vagina, ovaries, mammary glands, testes, vas deferens, seminal vesicles, prostate, and penis

Table 19.1: (continued)

Organ System	Function	Organs, Tissues, and Structures Involved
Respiratory	Delivery of air to sites where gas exchange can occur between the blood and cells (around body) or blood and air (lungs)	Mouth, nose, pharynx, larynx, trachea, bronchi, lungs, and diaphragm
Skeletal	Support and protection of soft tissues of body; movement at joints; production of blood cells; mineral storage	Bones, cartilage, ligaments
Urinary	Removal of excess water, salts, and waste products from blood and body; control of pH	Kidneys, ureters, urinary bladder, and urethra
Immune	Defending against microbial pathogens (disease-causing agents) and other diseases	Leukocytes, tonsils, adenoids, thymus, and spleen

Lesson Summary

- Not all cells are alike in a multicellular organism, but all of the cells in a multicellular organism have the same DNA.
- Each specialized cell has a specific function in the body. Specialized cells group together to carry out a specific function.
- Every cell in the body originated from a single zygote. The unspecialized zygote differentiates to produce specialized cells that work together and make up the body.
- A cell that is able to differentiate into all cell types within a body is totipotent. Embryonic stem cells are totipotent.
- A cell that is able to differentiate into many cell types, but not all types, is pluripotent. Adult stem cells and cord blood stem cells are pluripotent.
- A tissue is a group of connected cells that have a similar function within an organism. There are four basic types of tissue in the body of all animals: connective, muscle, nervous, and epithelial.
- An organ is a structure made of two or more different types of tissue that work together for a common purpose.
- An organ system is a group of organs that act together to carry out complex related functions, with each organ focusing on a part of the task.

Review Questions

1. Give three examples of specialized cells.
2. Contrast specialized cells and stem cells.
3. Name three sources of stem cells.
4. List the four tissue types that are found in the human body, and give an example of each type.
5. These cells form the lining of the trachea. Identify the cells and the type of tissue of which the ciliated cells in **Figure** 19.5 are a part.

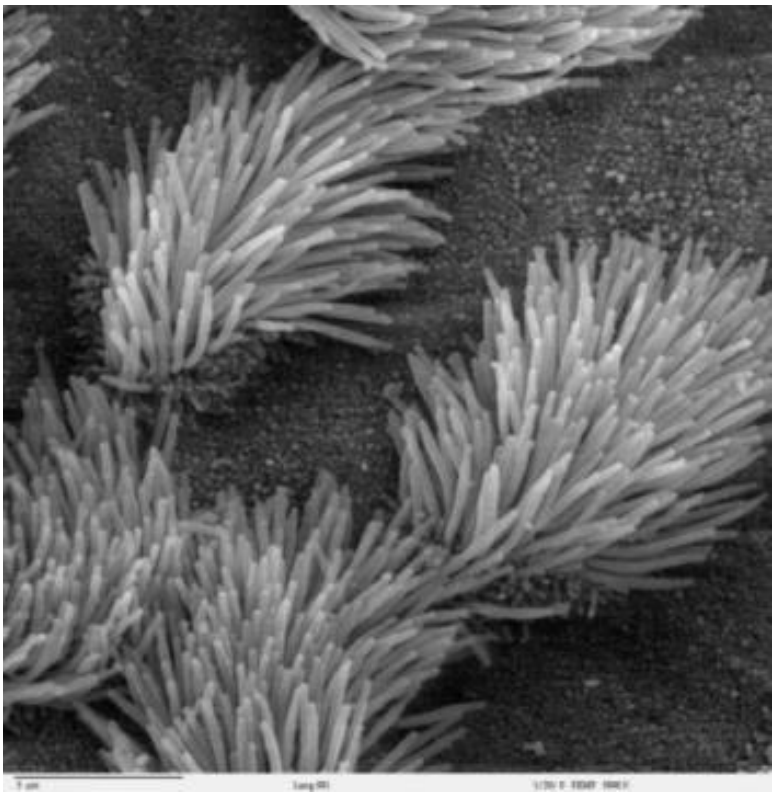


Figure 19.5

6. Summarize the relationship between tissues and organs.
7. Identify an organ that is part of two body systems.
8. A classmate says that the lymphatic system should not be an organ system in its own right, and is a part of the cardiovascular system. Do you agree or disagree with your classmate? Explain your answer by using your knowledge of organ systems.

Further Reading / Supplemental Links

- *Human Anatomy* ©2003 by Fredric H. Martini, Inc. and Michael J.Timmons. Published by Pearson Education, Inc.
- http://web.jjay.cuny.edu/~acarpi/NSC/14-anatomy.htm
- http://en.wikipedia.org

Vocabulary

adult stem cells Undifferentiated cells that are found within the body and that divide to replace dying cells and damaged tissues.

cell The most basic unit of life; basic unit of structure and function in living organisms.

differentiation The process by which an unspecialized cell (such as a fertilized egg cell), divides many times to produce specialized cells that work together and make up the body.

embryonic stem cells Stem cells found in embryos that can divide indefinitely, and specialize into any cell type.

organ A structure made of two or more tissues that work together for a common purpose.

organ system A group of organs that act together to carry out complex interrelated functions, with each organ focusing on a part of the task.

pluripotent A term that describes a cell that is able to differentiate into many cell types, but not all, within a body.

stem cell An unspecialized cell that can divide many times and give rise to different, specialized cells is called a stem cell.

tissue A group of connected cells that have a similar function within an organism.

totipotent A term that describes a cell that is able to differentiate into all cell types within a body.

Points to Consider

- The smallest unit capable of carrying out life processes in your body is a single cell. Cells organize into tissues, which organize into organs. Groups of organs work together as organ systems. Consider how the last meal you consumed is interacting with each level of organization in your body.
- Think about the advantages and disadvantages of having a body composed of many small cells as opposed to a single large cell.

19.2 Lesson 19.2: Homeostasis and Regulation

Lesson Objectives

- Identify the process by which body systems are kept within certain limits.
- Explain the role of feedback mechanisms in homeostasis.
- Distinguish negative feedback from positive feedback.
- Identify and example of two organ systems working together to maintain homeostasis.
- Summarize the role of the endocrine system in homeostasis.
- Outline the result of a disturbance in homeostasis of a body system.

Introduction

The human body is made up of trillions of cells that all work together for the maintenance of the entire organism. While cells, tissues, and organs may perform very different functions, all the cells in the body are similar in their metabolic needs. Maintaining a constant internal environment by providing the cells with what they need to survive (oxygen, nutrients, and removal of waste) is necessary for the well-being of individual cells and of the entire body. The many processes by which the body controls its internal environment are collectively called homeostasis. The complementary activity of major body systems maintains homeostasis.

Homeostasis

Homeostasis refers to stability, balance, or equilibrium within a cell or the body. It is an organism's ability to keep a constant internal environment. Homeostasis is an important characteristic of living things. Keeping a stable internal environment requires constant adjustments as conditions change inside and outside the cell. The adjusting of systems within a cell is called homeostatic regulation. Because the internal and external environments of a cell are constantly changing, adjustments must be made continuously to stay at or near the set point (the normal level or range). Homeostasis can be thought of as a dynamic equilibrium rather than a constant, unchanging state.

Feedback Regulation Loops

The endocrine system plays an important role in homeostasis because hormones regulate the activity of body cells. The release of hormones into the blood is controlled by a stimulus. For example, the stimulus either causes an increase or a decrease in the amount of hormone secreted. Then, the response to a stimulus changes the internal conditions and may itself become a new stimulus. This self-adjusting mechanism is called feedback regulation.

Feedback regulation occurs when the response to a stimulus has an effect of some kind on the original stimulus. The type of response determines what the feedback is called. **Negative feedback** occurs when the response to a stimulus reduces the original stimulus. **Positive feedback** occurs when the response to a stimulus increases the original stimulus.

Thermoregulation: A Negative Feedback Loop

Negative feedback is the most common feedback loop in biological systems. The system acts to reverse the direction of change. Since this tends to keep things constant, it allows the maintenance of homeostatic balance. For instance, when the concentration of carbon dioxide in the human body increases, the lungs are signaled to increase their activity and exhale more carbon dioxide, (your breathing rate increases). Thermoregulation is another example of negative feedback. When body temperature rises, receptors in the skin and the hypothalamus sense the temperature change. The temperature change (stimulus) triggers a command from the brain. This command, causes a response (the skin makes sweat and blood vessels near the skin surface dilate), which helps decrease body temperature. **Figure** 19.6 shows how the response to a stimulus reduces the original stimulus in another of the body's negative feedback mechanisms.

Positive feedback is less common in biological systems. Positive feedback acts to speed up the direction of change. An example of positive feedback is lactation (milk production). As the baby suckles, nerve messages from the mammary glands cause the hormone prolactin, to be secreted by the pituitary gland. The more the baby suckles, the more prolactin is released, which stimulates further milk production.

Not many feedback mechanisms in the body are based on positive feedback. Positive feedback speeds up the direction of change, which leads to increasing hormone concentration, a state that moves further away from homeostasis.

System Interactions

Each body system contributes to the homeostasis of other systems and of the entire organism. No system of the body works in isolation and the well-being of the person depends upon the well-being of all the interacting body systems. A disruption within one system generally has consequences for several additional body systems. Most of these organ systems are controlled

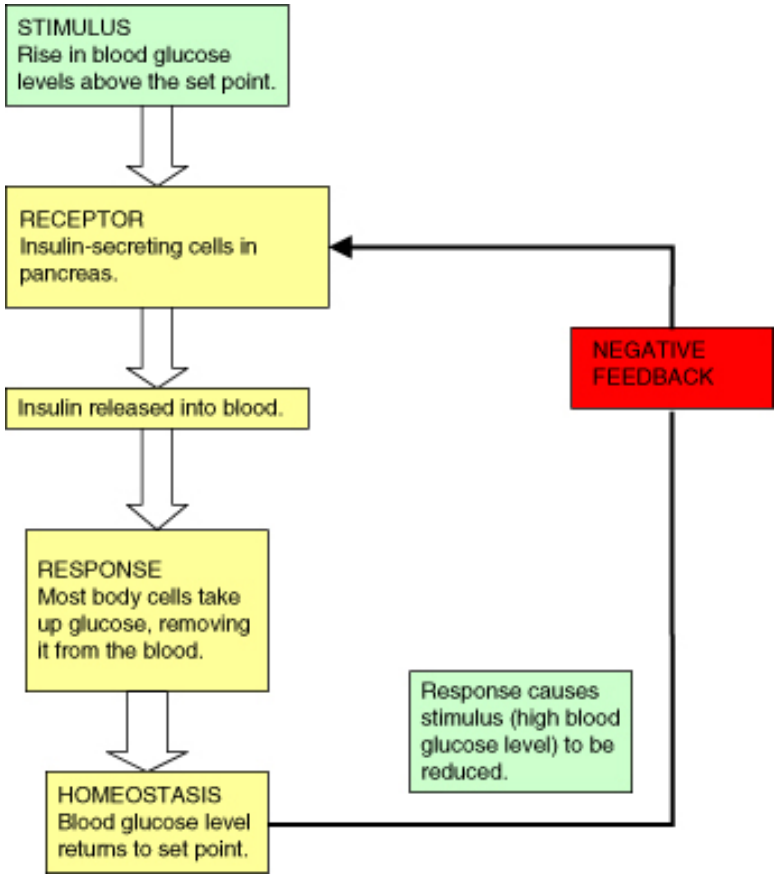


Figure 19.6: Control of blood glucose level is an example of negative feedback. Blood glucose concentration rises after a meal (the stimulus). The hormone insulin is released by the pancreas, and it speeds up the transport of glucose from the blood and into selected tissues (the response). Blood glucose concentrations then decrease, which then decreases the original stimulus. The secretion of insulin into the blood is then decreased.

by hormones secreted from the pituitary gland, a part of the endocrine system. **Table** 19.2 summarizes how various body systems work together to maintain homeostasis.

Main examples of homeostasis in mammals are as follows:

- The regulation of the amounts of water and minerals in the body. This is known as osmoregulation. This happens primarily in the kidneys.
- The removal of metabolic waste. This is known as excretion. This is done by the excretory organs such as the kidneys and lungs.
- The regulation of body temperature. This is mainly done by the skin.
- The regulation of blood glucose level. This is mainly done by the liver and the insulin and glucagon secreted by the pancreas in the body.

Table 19.2: **Types of Homeostatic Regulation in the Body**

	Homeostatic Processes	Hormones and Other Messengers	Tissues, Organs and Organ Systems Involved
Osmoregulation (also called excretion)	Excess water, salts, and urea expelled from body	Antidiuretic hormone (ADH), aldosterone, angiotensin II, carbon dioxide	Kidneys, urinary bladder, ureters, urethra (urinary system), pituitary gland (endocrine system), lungs (respiratory system)
Thermoregulation	Sweating, shivering, dilation/constriction of blood vessels at skin surface, insulation by adipose tissue, breakdown of adipose tissue to produce heat	Nerve impulses	Skeletal muscle (muscular system), nerves (nervous system), blood vessels (cardiovascular system), skin and adipose tissue (integumentary system), hypothalamus (endocrine system)

Table 19.2: (continued)

	Homeostatic Processes	Hormones and Other Messengers	Tissues, Organs and Organ Systems Involved
Chemical Regulation (including glucoregulation)	Release of insulin and glucagon into the blood in response to rising and falling blood glucose levels, respectively; increase in breathing rate in response to increases carbon dioxide levels in the blood, and release of carbon dioxide into exhaled air from lungs, secretion of erythropoietin by kidneys to stimulate formation of red blood cells	Insulin, glucagon, cortisol, carbon dioxide, nerve impulses, erythropoietin (EPO)	Pancreas (endocrine system), liver (digestive system); adrenal glands (endocrine system) lungs (respiratory system), brain (nervous system), kidneys (urinary system)

Endocrine System

The endocrine system, shown in **Figure** 20.39, includes glands which secrete hormones into the bloodstream. Hormones are chemical messenger molecules that are made by cells in one part of the body and cause changes in cells in another part of the body. The endocrine system regulates the metabolism and development of most body cells and body systems through feedback mechanisms. For example, Thyrotropin-Releasing Hormone (TRH) and Thyroid Stimulating Hormone (TSH) are controlled by a number of negative feedback mechanisms. The endocrine glands also release hormones that affect skin and hair color, appetite, and secondary sex characteristics of males and females.

The endocrine system has a regulatory effect on other organ systems in the human body. In the muscular system, hormones adjust muscle metabolism, energy production, and growth. In the nervous system, hormones affect neural metabolism, regulate fluid and ion concentration and help with reproductive hormones that influence brain development.

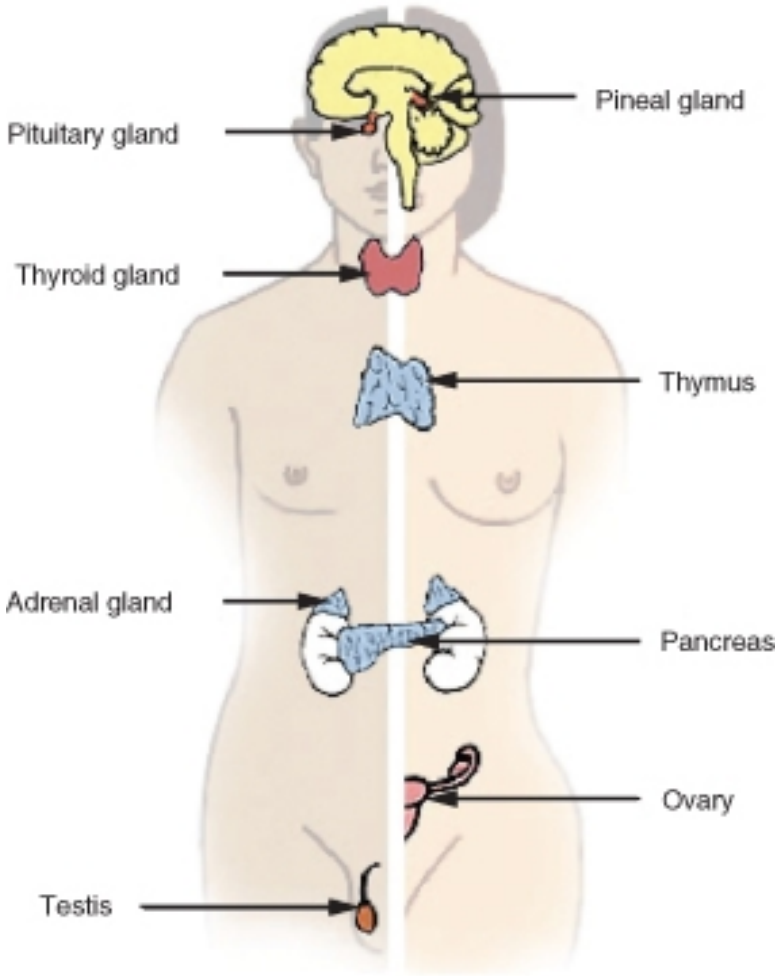


Figure 19.7: The endocrine system controls almost every other body system through feedback mechanisms. Most of the mechanisms of the endocrine system are negative feedback.

Urinary System

Toxic wastes build up in the blood as proteins and nucleic acids are broken down and used by the body. The urinary system rids the body of these wastes. The urinary system is also directly involved in maintaining proper blood volume. The kidneys also play an important role in maintaining the correct salt and water content of the body. External changes, such as a warm weather, that lead to excess fluid loss trigger feedback mechanisms that act to maintain the body's fluid content by inhibiting fluid loss. The kidneys also produce a hormone called erythropoietin, also known as EPO, which stimulates red blood cell production.

Reproductive System

The reproductive system does little for the homeostasis of the organism. The reproductive system relates instead to the maintenance of the species. However, sex hormones do have an effect on other body systems, and an imbalance in sex hormones can lead to various disorders. For example, a woman whose ovaries are removed early in life is at higher risk of developing osteoporosis, a disorder in which bones are thin and break easily. The hormone estrogen, produced by the ovaries, is important for bone growth. Therefore, a woman who does not produce estrogen will have impaired bone development.

Disruption of Homeostasis

Many homeostatic mechanisms keep the internal environment within certain limits (or set points). When the cells in your body do not work correctly, homeostatic balance is disrupted. Homeostatic imbalance may lead to a state of disease. Disease and cellular malfunction can be caused in two basic ways: by deficiency (cells not getting all they need) or toxicity (cells being poisoned by things they do not need). When homeostasis is interrupted, your body can correct or worsen the problem, based on certain influences. In addition to inherited (genetic) influences, there are external influences that are based on lifestyle choices and environmental exposure. These factors together influence the body's ability to maintain homeostatic balance. The endocrine system of a person with diabetes has difficulty maintaining the correct blood glucose level. A diabetic needs to check their blood glucose levels many times during the day, as shown in **Figure** 19.8, and monitor daily sugar intake.

Internal Influences: Heredity

Genetics: Genes are sometimes turned off or on due to external factors which we have some control over. Other times, little can be done to prevent the development of certain genetic diseases and disorders. In such cases, medicines can help a person's body regain homeostasis. An example is the metabolic disorder Type 1 diabetes, which is a disorder where the pancreas is no longer producing adequate amounts of insulin to respond to changes in a person's blood

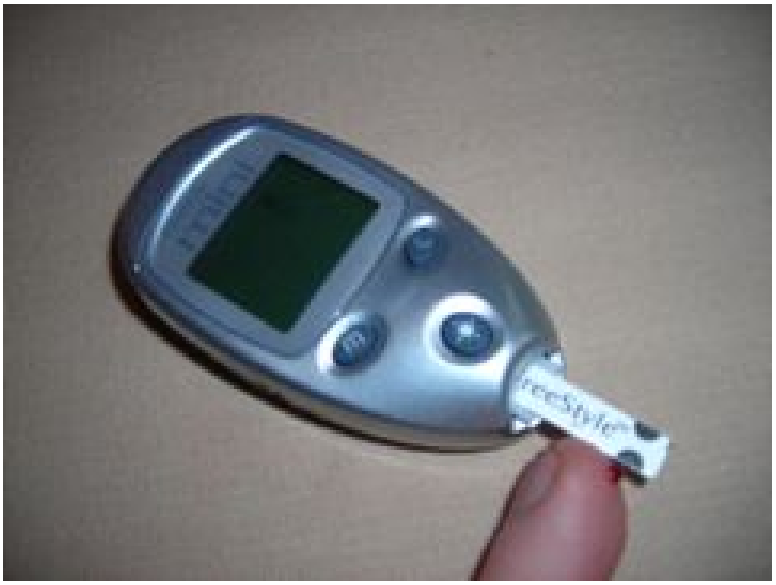


Figure 19.8: A person with diabetes has to monitor their blood glucose carefully. This glucose meter analyses only a small drop of blood. For an animation of diabetes, see (

glucose level. Insulin replacement therapy, in conjunction with carbohydrate counting and careful monitoring of blood glucose concentration, is a way to bring the body's handling of glucose back into balance. Cancer can be genetically inherited or be due to a mutation caused by exposure to toxin such as radiation or harmful drugs. A person may also inherit a predisposition to develop a disease such as heart disease. Such diseases can be delayed or prevented if the person eats nutritious food, has regular physical activity, and does not smoke.

External Influences: Lifestyle

Nutrition: If your diet lacks certain vitamins or minerals your cells will function poorly, and you may be at risk to develop a disease. For example, a menstruating woman with inadequate dietary intake of iron will become anemic. Hemoglobin, the molecule that enables red blood cells to transport oxygen, requires iron. Therefore, the blood of an anemic woman will have reduced oxygen-carrying capacity. In mild cases symptoms may be vague (e.g. fatigue), but if the anemia is severe the body will try to compensate by increasing cardiac output, leading to weakness, irregular heartbeats and in serious cases, heart failure.

Physical Activity: Physical activity is essential for proper functioning of our cells and bodies. Adequate rest and regular physical activity are examples of activities that influence homeostasis. Lack of sleep is related to a number of health problems such as irregular heartbeat, fatigue, anxiety, and headaches. Being overweight and obesity, two conditions that are related to poor nutrition and lack of physical activity greatly affect many organ

systems and their homeostatic mechanisms. Being overweight or obese increases a person's risk of developing heart disease, Type 2 diabetes, and certain forms of cancer. Staying fit by regularly taking part in aerobic activities such as walking, shown in **Figure** 19.9, has been shown to help prevent many of these diseases.

Figure 19.9: Adding physical activity to your routine can be as simple as walking for a total of 60 minutes a day, five times a week.

Mental Health: Your physical health and mental health are inseparable. Our emotions cause chemical changes in our bodies that have various effects on our thoughts and feelings. Negative stress (also called distress) can negatively affect mental health. Regular physical activity has been shown to improve mental and physical wellbeing, and helps people to cope with distress. Among other things, regular physical activity increases the ability of the cardiovascular system to deliver oxygen to body cells, including the brain cells. Medications that may help balance the amount of certain mood-altering chemicals within the brain are often prescribed to people who have mental and mood disorders. This is an example of medical help in stabilizing a disruption in homeostasis.

Environmental Exposure

Any substance that interferes with cellular function and causes cellular malfunction is a cellular toxin. There are many different sources of toxins, for example, natural or synthetic drugs, plants, and animal bites. Air pollution, another form of environmental exposure to toxins is shown in **Figure** 19.10. A commonly seen example of an exposure to cellular toxins is by a drug overdose. When a person takes too much of a drug that affects the central nervous system, basic life functions such as breathing and heartbeat are disrupted. Such disruptions can results in coma, brain damage, and even death.

Figure 19.10: Air pollution can cause environmental exposure to cellular toxins such as mercury.

The six factors described above have their effects at the cellular level. A deficiency or lack of beneficial pathways, whether caused by an internal or external influence, will almost always result in a harmful change in homeostasis. Too much toxicity also causes homeostatic imbalance, resulting in cellular malfunction. By removing negative health influences and providing adequate positive health influences, your body is better able to self-regulate and self-repair, which maintains homeostasis.

Lesson Summary

- Homeostasis is an organism's ability to maintain a stable internal environment. Homeostasis is an important characteristic of living things. Keeping a stable internal environment requires constant adjustments as conditions change inside and outside the cell.
- Feedback regulation mechanisms are important to homeostasis. Feedback regulation occurs when the response to a stimulus has an effect of some kind on the original stimulus. The type of response (increase or decrease in the stimulus) determines what the feedback is called.
- Negative feedback occurs when the response to a stimulus reduces the original stimulus. Positive feedback occurs when the response to a stimulus increases the original stimulus.
- No system of the body works in isolation, and the well-being of a person depends upon the well-being of all the interacting body systems. A disruption within one system generally has consequences for several additional body systems.
- The homeostatic balance of most organs and organ systems is controlled by hormones secreted from the pituitary gland, a part of the endocrine system.

- When the cells in your body do not work correctly, homeostatic balance is disrupted. Homeostatic imbalance may lead to a state of disease. Type 2 diabetes is a disease in which homeostasis of the blood glucose level is disturbed, leading to an imbalance that affect many other body systems, including the cardiovascular system.

Review Questions

1. Outline the importance of homeostasis to an organism.
2. How do feedback mechanisms help maintain homeostasis?
3. What is the difference between negative and positive feedback?
4. Identify and give an example of two organ systems working together to maintain homeostasis.
5. Summarize the role of the endocrine system in homeostasis.
6. Name two diseases that can result from an imbalance in body homeostasis.
7. Why is positive feedback not an effective way of controlling hormone levels?

Further Reading / Supplemental Links

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Vocabulary

homeostasis Stability, balance, or equilibrium within the cell or a body; an organism's ability to keep a constant internal environment.

negative feedback Occurs when the response to a stimulus reduces the original stimulus.

positive feedback Occurs when the response to a stimulus increases the original stimulus.

Points to Consider

- Negative feedback is most common feedback loop in biological systems. The system acts to reverse the direction of change. Positive feedback is less common in biological systems. The system acts to speed up the direction of change. Consider how your social interactions with teachers, parents and other students may be classified as either positive or negative feedback.
- When homeostasis is interrupted, your body can correct or worsen the problem, based on certain influences. In addition to genetic influences, there are external influences that are based on lifestyle choices and environmental exposures. Describe how your lifestyle may positively or negatively affect your body's ability to maintain homeostasis

Image Sources

(1) http://commons.wikimedia.org/wiki/File:Glucose_test.JPG. CC-BY-SA.

(2) http://en.wikipedia.org/wiki/Image:Stem_cell_division_and_differentiation.svg. Public Domain.

(3) Drs. Noguchi, Rodgers, and Schechter of NIDDK. *http://remf.dartmouth.edu/images/humanMuscleTEM/source/2.html* *http://commons.wikimedia.org/wiki/Image:Redbloodcells.jpg*. (a) Public Domain (b) Public Domain (d) Public Domain.

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Chapter 20

Nervous and Endocrine Systems

20.1 Lesson 20.1: The Nervous System

Lesson Objectives

- Identify the type of cells that make up nervous tissue.
- Describe the structure of a neuron.
- Relate membrane potential to action potential.
- Outline the role of neurotransmitters in neuron communication.
- Distinguish between the sensory and motor divisions of the peripheral nervous system.
- Describe the structure of the eye and identify the roles of rods and cones in vision.
- Describe the structure of the ear and identify the structures that are important to hearing and balance.
- Distinguish between the receptors for pain, pressure, and temperature.
- Identify the main effect of psychoactive drugs on the CNS.
- Summarize the mechanism of addiction.

Introduction

Your body has two systems that help you maintain homeostasis: the nervous system and the endocrine system. The **nervous system** is a complex network of nervous tissue that sends electrical and chemical signals. The nervous system includes the central nervous system (CNS) and the peripheral nervous system (PNS) together. The **central nervous system** is made up of the brain and spinal cord, and the **peripheral nervous system** is made up of the nervous tissue that lies outside the CNS, such as the nerves in the legs, arms, hands, feet and organs of the body. The nervous system mediates communication between different parts of the body as well as the body's interactions with the environment.

The **endocrine system** is a system of glands around the body that release chemical signal molecules into the bloodstream. The electrical signals of the nervous system move very rapidly along nervous tissue, while the chemical signals of the endocrine system act slowly in comparison and over a longer period of time. Working together, the nervous and endocrine systems allow your body to respond to short or long term changes in your environment, such as a pedestrian suddenly stepping out in front of your bike, or your body adapting to cycling in a warm, humid summer evening, as shown in **Figure** 20.1.

Figure 20.1: Cycling home in rush-hour traffic demands a lot of your nervous and endocrine systems. Your nervous system—mostly through your eyes and ears—constantly monitors your surroundings, alerting you instantly at any sign of change or danger. Your endocrine system gears up your muscles and cardiovascular system for the ride, by flooding your body with metabolism-boosting hormones.

Nerve Cells

Although the nervous system is very complex, there are only two main types of nerve cells in nervous tissue. All parts of the nervous system are made of nervous tissue. The **neuron**

is the "conducting" cell that transmits electrical signals, and it is the structural unit of the nervous system. The other type of cell is a glial cell. **Glial cells** provide a support system for the neurons, and recent research has discovered they are involved in synapse formation. A type of glial cell in the brain, called **astrocytes**, is important for the maturation of neurons and may be involved in repairing damaged nervous tissue. Neurons and glial cells make up most of the brain, the spinal cord and the nerves that branch out to every part of the body. Both neurons and glial cells are sometimes referred to as nerve cells.

Structure of a Neuron

The special shape of a neuron allows it to pass an electrical signal to another neuron, and to other cells. Electrical signals move rapidly along neurons so that they can quickly pass "messages" from one part of the body to another. These electrical signals are called nerve impulses.

Neurons are typically made up of a cell body (or soma), dendrites, and an axon, as shown in **Figure** 20.2. The cell body contains the nucleus and other organelles similar to other body cells. The **dendrites** extend from the cell body and receive a nerve impulse from another cell. The cell body collects information from the dendrites and passes it along to the axon. The **axon** is a long, membrane-bound extension of the cell body that passes the nerve impulse onto the next cell. The end of the axon is called the **axon terminal**. The axon terminal is the point at which the neuron communicates with the next cell. You can say the dendrites of the neuron receive the information, the cell body gathers it, and the axons pass the information onto another cell.

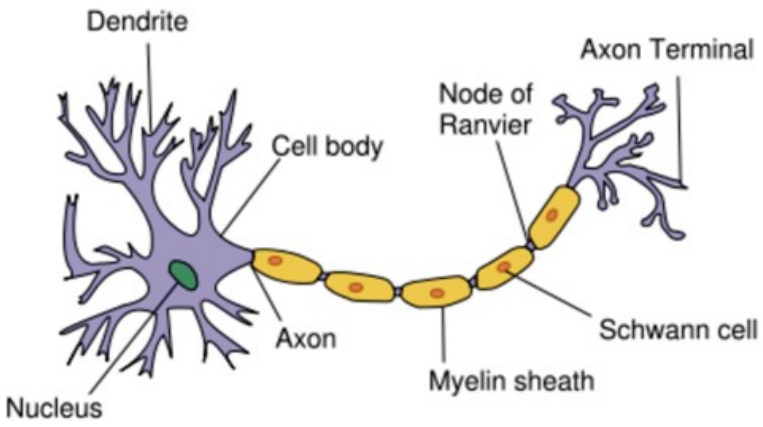

Figure 20.2: The general structure of a neuron. Neurons come in many different shapes and sizes, but they all have a cell body, dendrites, and an axon. The cell body contains a nucleus and other organelles. However, not all neurons have a myelin sheath.

The axons of many neurons are covered with an electrically insulating phospholipid layer called a **myelin sheath**. The myelin speeds up the transmission of a nerve impulse along

the axon. It acts like a layer of insulation, like the plastic you would see around an electrical cord.

The myelin is an outgrowth of glial cells. **Schwann cells** which are shown wrapped around the neuron in **Figure** 20.2, are a type of glial cell. Schwann cells are flat and thin, and like other cells, contain a nucleus and other organelles. Schwann cells supply the myelin for neurons that are not part of the brain or spinal cord, while another type of glial cell, called **oligodendrocytes**, supply myelin to those of the brain and spinal cord. Myelinated neurons are white in appearance, and they are what makes up the "white matter" of the brain. A cross section of a myelinated neuron is shown in **Figure** 20.3. Myelin is not continuous along the axon. The regularly spaced gaps between the myelin are called **Nodes of Ranvier**. The nodes are the only points at which ions can move across the axon membrane, through ion channels. In this way the nodes act to strengthen the nerve impulse by concentrating the flow of ions at the nodes of Ranvier along the axon.

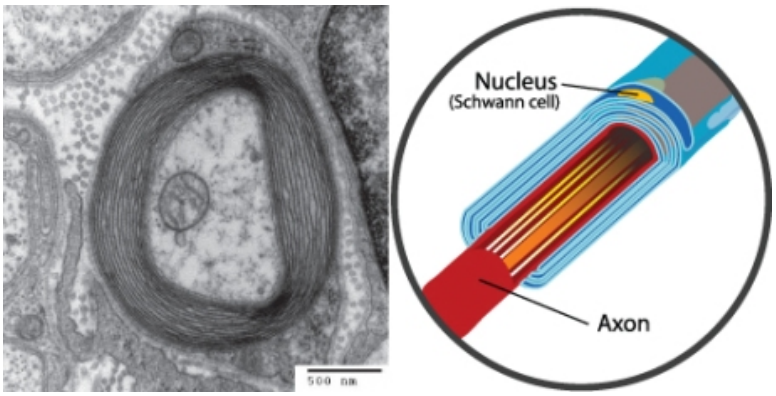

Figure 20.3: A transmission electron microscope (TEM), image of a cross section of a myelinated axon. The "rings" around the axon are made up of Schwann cell membrane, which is wrapped many times around the axon.

Neurons are specialized for the passing of cell signals. Given the many functions carried out by neurons in different parts of the nervous system, there are many different of shapes and sizes of neurons. For example, the cell body of a neuron can vary from 4 to 100 micrometers in diameter. Some neurons can have over 1,000 dendrite branches, which make connections with tens of thousands of other cells. Other neurons have only 1 or 2 dendrites, each of which has thousands of synapses. A **synapse** is a specialized junction at which neurons communicate with each other, and is shown in **Figure** 20.4. Also, a neuron may have 1 or many axons. The longest axon of a human motor neuron can be over a meter long, reaching from the base of the spine to the toes. Sensory neurons have axons that run from the toes to the spinal cord, over 1.5 meters in adults. Giraffes have single axons several meters in length running along the entire length of their necks.

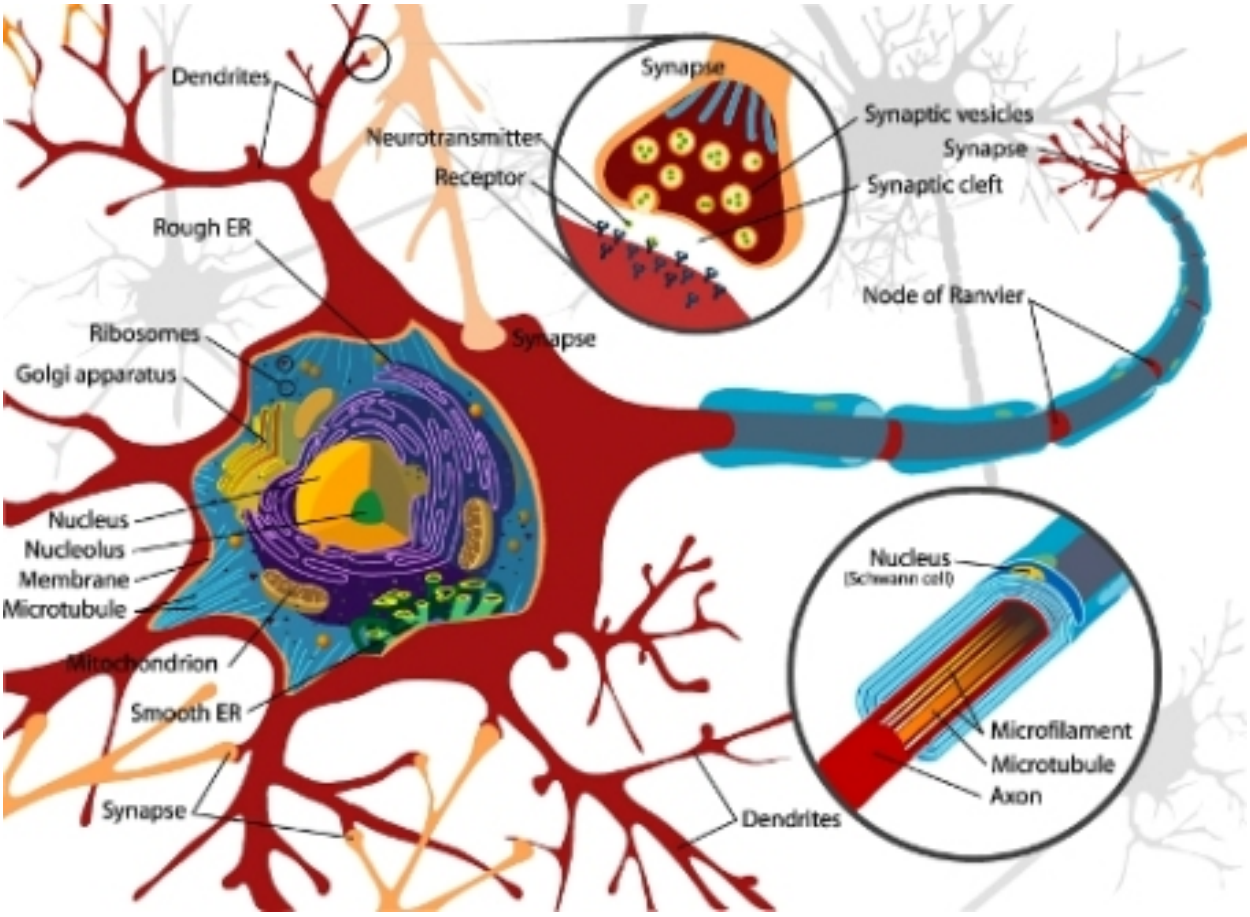

Figure 20.4: The location of synapses. Synapses are found at the end of the axons (called axon terminals) and help connect a single neuron to thousands of other neurons. Chemical messages called neurotransmitters are released at the synapse and pass the "message" onto the next neuron or other type of cell.

Nerve Impulses

In the late 18th century, the Italian doctor and physicist Luigi Galvani first recorded the action of electricity on the muscle tissue of frogs. He noted that an electrical charge applied to a nerve in the legs of a dead frog made the legs move. Galvani attributed the movement of the frog's muscles to an electrical current that was carried by the nerves. Galvani coined the term "animal electricity" to describe this vital force for life.

Galvani believed that animal electricity came from the muscle and was unique to living creatures. However, his fellow Italian, and physicist, Alessandro Volta disagreed with him and reasoned that animal electricity was a physical phenomenon, that occurred between metals. Volta disproved Galvani's claim by building the first battery, which showed that a current could flow outside an organism's body. Since then scientists have learned much about electrical charges in living systems.

Ion Channels and Nerve Impulses

Ion transport proteins have a special role in the nervous systems because voltage-gated ion channels and ion pumps are essential for forming a nerve impulse. Ion channels use energy to build and maintain a concentration gradient of ions between the extracellular fluid and the cell's cytosol, as shown in **Figure** 20.5. This concentration gradient results in a net negative charge on the inside of the membrane and a positive charge on the outside. Ion channels and ion pumps are very specific; they allow only certain ions through the cell membrane. For example, potassium channels will allow only potassium ions through, and the **sodium-potassium pump** acts only on sodium and potassium ions.

All cells have an electrical charge which is due to the concentration gradient of ions that exists across the membrane. The number of positively charged ions outside the cell membrane is greater than the number of positively charged ions in the cytosol. This difference causes a voltage difference across the membrane. **Voltage** is electrical potential energy that is caused by a separation of opposite charges, in this case across the membrane. The voltage across a membrane is called **membrane potential**. Membrane potential is the basis for the conduction of nerve impulses along the cell membrane of neurons. Ions that are important in the formation of a nerve impulse include sodium (Na^+) and potassium (K^+).

Resting Potential

When a neuron is not conducting a nerve impulse, it is said to be at rest. The **resting potential** is the resting state of the neuron, during which the neuron has an overall negative charge. In neurons the resting potential is approximately -70 milliVolts (mV). The negative sign indicates the negative charge inside the cell relative to the outside.

The reasons for the overall negative charge of the cell include:

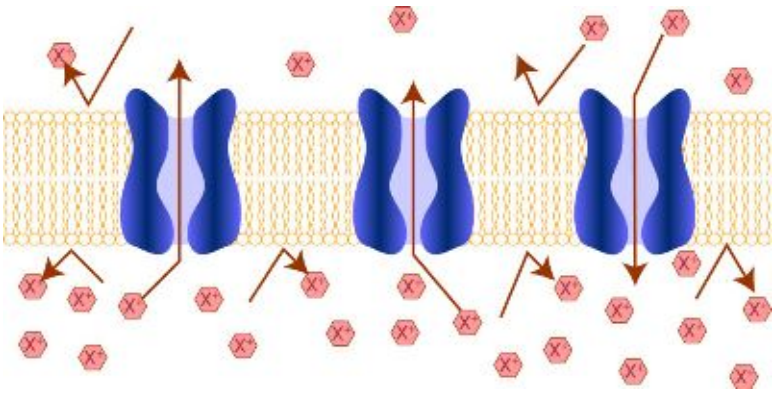

Figure 20.5: Channel proteins in the plasma membrane. Membrane channel proteins (or channel proteins), allow the movement of specific ions across the cell membrane, in this case the hypothetical "X" ion. The concentration gradient results in electrical potential energy building up across the membrane, the basis for the conduction of a nerve impulse.

- The sodium-potassium pump removes Na^+ ions from the cell by active transport. A net negative charge inside the cell is due to the higher concentration of Na^+ ions outside the cell than inside the cell.
- Most cells have potassium-selective ion channel proteins that remain open all the time. The K^+ ions move down the concentration gradient (passively) through these potassium channels and out of the cell, which results in a build-up of excess positive charge outside of the cell.
- There are a number of large, negatively charged molecules, such as proteins, inside the cell.

Action Potential

An **action potential** is an electrical charge that travels along the membrane of a neuron. It can be generated when a neuron's membrane potential is changed by chemical signals from a nearby cell. In an action potential, the cell membrane potential changes quickly from negative to positive as sodium ions flow into and potassium ions flow out of the cell through ion channels, as shown in **Figure** 20.6.

The change in membrane potential results in the cell becoming depolarized. An action potential works on an all-or-nothing basis. That is, the membrane potential has to reach a certain level of depolarization, called the **threshold**, otherwise an action potential will not start. This threshold potential varies, but is generally about 15 millivolts (mV) more positive than the cell's resting membrane potential. If a membrane depolarization does not reach the threshold level, an action potential will not happen. You can see in **Figure** 20.7 how two depolarizations did not reach the threshold level of -55mV. The first channels to open are the sodium ion-channels, which allow sodium ions to enter the cell. The resulting increase in

positive charge inside the cell (up to about +40 mV) starts the action potential. Potassium ion-channels then open up, allowing potassium ions out of the cell, which ends the action potential. Both of the ion channels then close, and the sodium-potassium pump restores the resting potential of -70 mV. The action potential will move down the axon toward the synapse like a wave would move along the surface of water.

In myelinated neurons, ion flows occur only at the nodes of Ranvier. As a result, the action potential signal "jumps" along the axon membrane, from node to node, rather than spreading smoothly along the membrane, as they do in axons that do not have a myelin sheath. This is due to clustering of Na^+ and K^+ ion channels at the Nodes of Ranvier. Unmyelinated axons do not have Nodes of Ranvier; and ion channels in these axons are spread over the entire membrane surface.

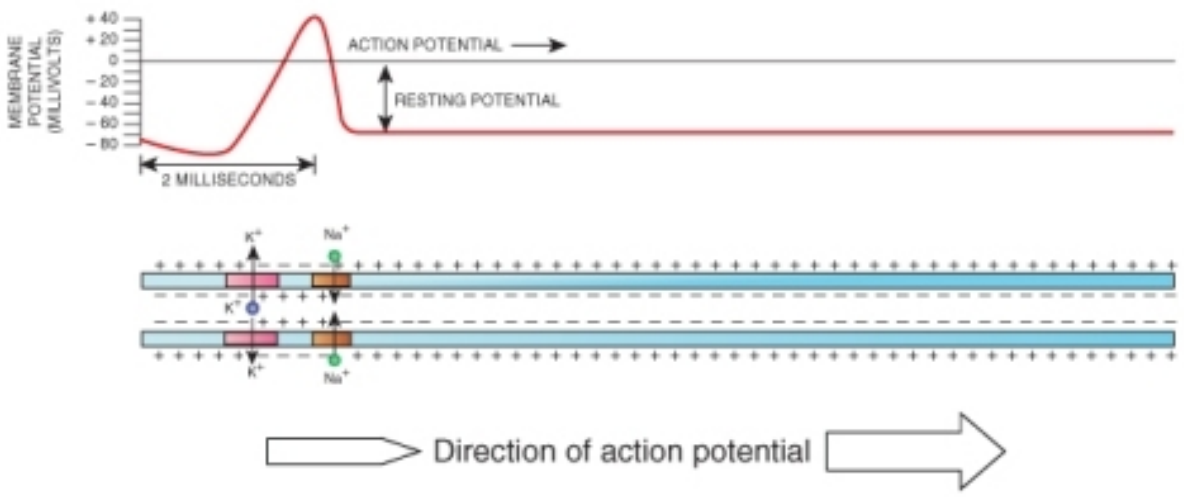

Figure 20.6: The movement of an action potential down an axon. A chemical message from another nerve causes the sodium ion channels at one point in the axon to open. Sodium ions rush across the membrane and cause the interior of the axon to become positively charged (depolarized) because the cell now contains more positive charges. Potassium ion channels then open and potassium ions flow out of the cell, which end the action potential. The action potential then moves down the axon membrane toward the synapse.

Types of Neurons

Neurons are highly specialized for the processing and transmission of cellular signals and can be classified by their structure or function. Structural classification is based on the number

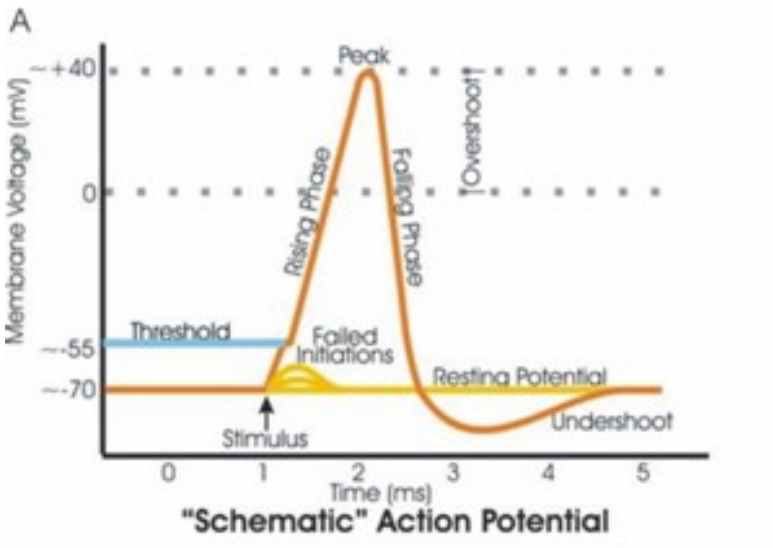

Figure 20.7: The changes in membrane potential during an action potential. Note the failed initiations that did not start an action potential. These depolarizations did not reach the threshold level (of about -55mV), so they did not start an action potential.

of dendrites and axons that a cell has. Functional classification groups neurons according to the direction in which the nerve impulse is moving in relation to the CNS.

We will discuss the three functional groups of nerves:

- **Sensory neurons** carry signals from tissues and organs to the central nervous system and are sometimes also called afferent neurons. Sensory neurons typically have a long dendrite and short axon. Sensory neurons are found in reflex arcs and are involved in several forms of involuntary behavior, including pain avoidance.
- **Motor neurons** carry signals from the central nervous system to muscles and glands and are sometimes called efferent neurons. Motor neurons have a long axon and short dendrites.
- **Interneurons** connect sensory and motor neurons in neural pathways that go through the central nervous system. Interneurons are also called association or relay neurons. Interneurons are found only in the central nervous system where they connect neuron to neuron.

Communication Between Neurons

Neurons communicate with each other at specialized junctions called synapses. Synapses are also found at junctions between neurons and other cells, such as muscle cells like the one shown in **Figure** 20.8. To see a synapse between two neurons, refer to **Figure** 20.4.

There are two types of synapses:

- **chemical synapses** use chemical signaling molecules as messengers
- **electrical synapses** use ions as messengers

We will primarily discuss chemical synapses in this chapter. The axon terminal of one neuron usually does not touch the other cell at a chemical synapse. Between the axon terminal and the receiving cell is a gap called a **synaptic cleft**. The transmitting cell is called the presynaptic neuron, and the receiving cell is called the postsynaptic cell or if it is another neuron, a postsynaptic neuron.

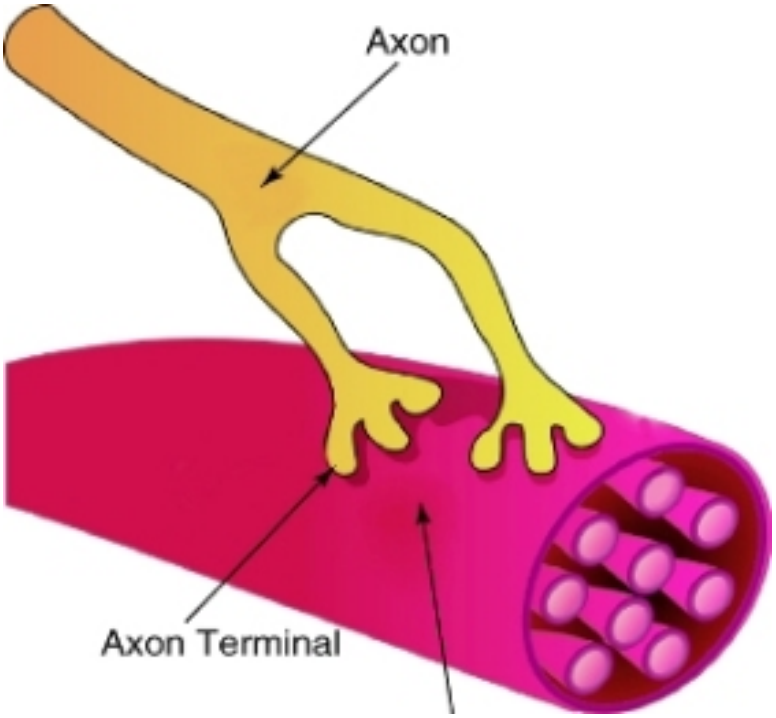

Figure 20.8: A synapse between a neuron and a muscle cell. The connection between a neuron and a muscle cell, called a . The finger-like projections of the axon are the axon terminals. An action potential moves down to the axon terminals where it causes a chemical message called a neurotransmitter to be released into the synaptic cleft. The neurotransmitter then causes an action potential to start on the membrane of the muscle cell.

Your brain has a huge number of synapses. Each of your 10^{12} (one trillion) neurons—including glial cells—has on average 7,000 synaptic connections to other neurons. It has been estimated that the brain of a three-year-old child has about 10^{16} synapses (10 quadrillion). This number declines with age, and levels off by adulthood. An adult has between 10^{15} and 5 x 10^{15} synapses (1 to 5 quadrillion).

Neurotransmitter Release

When an action potential reaches the axon terminal, it causes the neurotransmitter vesicles to fuse with the terminal membrane, and the neurotransmitter is released into the synaptic cleft. A **neurotransmitter** is a chemical message that is used to relay electrical signals between a neuron and another cell. Neurotransmitter molecules are made inside the presynaptic neuron and stored in vesicles at the axon terminal. Some neurons make only one type of neurotransmitter, but most neurons make two or more types of neurotransmitters.

When an action potential reaches the axon terminal, it causes the neurotransmitter vesicles to fuse with the terminal membrane. Neurotransmitter is released into the synaptic cleft. The neurotransmitters then diffuse across the synaptic cleft and bind to receptor proteins on the membrane of the postsynaptic cell, as shown in **Figure** 20.9.

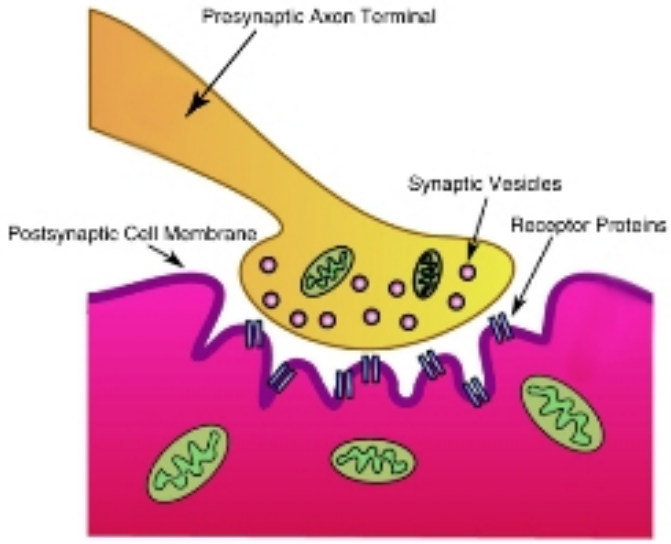

Figure 20.9: The synaptic cleft. Neurotransmitter that is released into the synaptic cleft diffuses across the synaptic membrane and binds to its receptor protein on the post synaptic cell.

Neurotransmitter Action

Many types of neurotransmitters exist, a few of which are listed in **Table** 20.1. Neurotransmitters can have an excitatory or inhibitory effect on the postsynaptic cell. An excitatory neurotransmitter initiates an action potential and an inhibitory neurotransmitter prevents

one from starting. Glutamate is the most common excitatory transmitter in the body while GABA and glycine are inhibitory neurotransmitters. The release of acetylcholine, an excitatory neurotransmitter causes an inflow of positively charged sodium ions (Na^+) into the postsynaptic neuron. This inflow of positive charge causes a depolarization of the membrane at that point. The depolarization then spreads to the rest of the postsynaptic neuron. Acetylcholine is the neurotransmitter that initiates muscle movement.

The effect of a neurotransmitter also can depend on the receptor it binds to. That is, a single neurotransmitter may be excitatory to the receiving neuron, or it may inhibit such an impulse by causing a change in the membrane potential of the cell. Synapses too can be excitatory or inhibitory and will either increase or decrease activity in the target neuron, based on the opening or closing of ion channels.

Table 20.1: **Common Neurotransmitters and Their Receptors**

Name	Receptor Name and Type	Ions Involved
Glutamate (glutamic acid)	Glutamate receptors (ligand-gated ion channels and G protein-coupled receptors)	Ca2+, K+, Na+
Acetylcholine	Acetylcholine receptors (ligand-gated ion channel)	Na+
Norepinephrine (noradrenaline)	Adrenoceptors (G protein-coupled receptors)	Ca2+
Epinephrine (adrenaline)	Adrenoceptors (G protein-coupled receptors)	Ca2+
Serotonin (5-hydroxytryptamine)	5-HT receptors 5-HT_3 is a ligand-gated ion channel 5-HT_1, 5-HT_2, 5-HT_4, 5-HT_5A, 5-HT_7 are G protein-coupled receptors	K+, Na+
Gamma-aminobutyric acid (GABA)	$GABA_A$ and $GABA_C$ (ligand-gated ion channels) $GABA_B$ (G protein-coupled receptors)	Cl- K+
Histamine	Histamine receptors (H1, H2, H3, H4) (G protein-coupled receptors)	

Neurotransmitter receptors can be gated ion channels that open or close through neurotransmitter binding or they can be protein-linked receptors. Protein-linked receptors are

not ion channels; instead they cause a signal transduction that involves enzymes and other molecules (called second messengers) in the postsynaptic cell. Refer to the *Cell Structure and Function* chapter for more information about signal transduction mechanisms.

Neurotransmitter Reuptake

Many neurotransmitters are removed from the synaptic cleft by neurotransmitter transporters in a process called reuptake. **Reuptake** is the removal of a neurotransmitter from the synapse by the pre-synaptic neuron. Reuptake happens after the neurotransmitter has transmitted a nerve impulse. Without reuptake, the neurotransmitter molecules might continue to stimulate or inhibit an action potential in the post-synaptic neuron. The process of release and reuptake of neurotransmitters is shown in **Figure** 20.10.

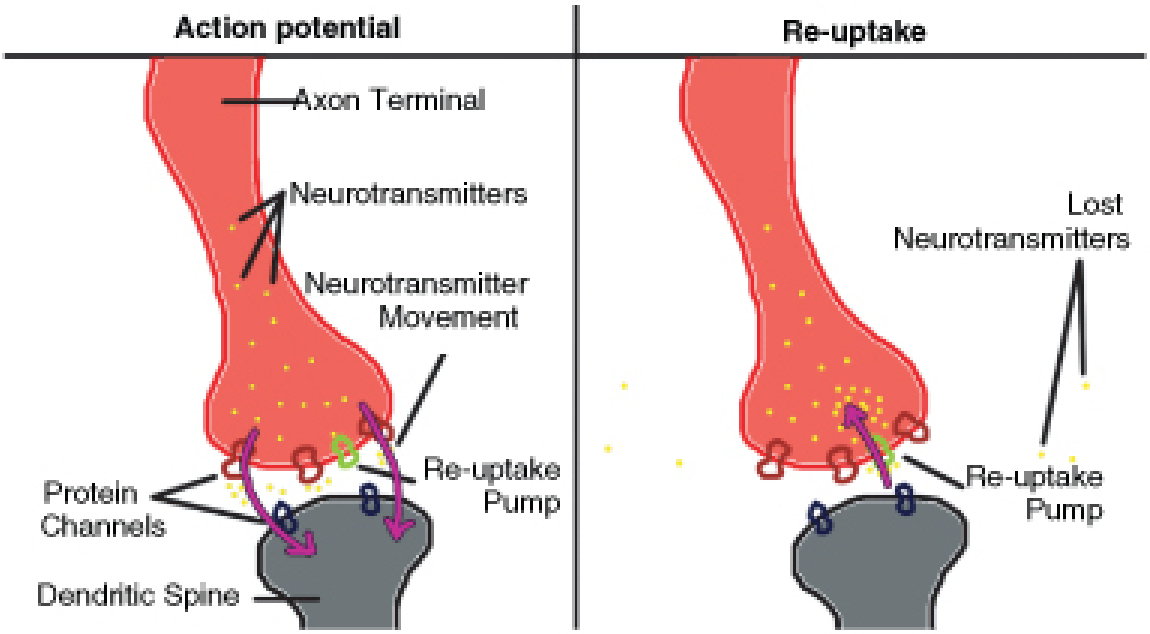

Figure 20.10: A synapse before and during reuptake. Neurotransmitter transporter proteins (also called reuptake pumps) release the neurotransmitter and also reuptake it from the synaptic cleft. Reuptake is a way of controlling the effect the neurotransmitter has on the post-synaptic cell.

Re-uptake is carried out by transporter proteins which bind to the released transmitter and actively transport it across the plasma membrane into the pre-synaptic neuron. The reuptake of neurotransmitter is the target of some types of medicine. For example, serotonin is a neurotransmitter that is produced by neurons in the brain. Serotonin is believed to

play an important role in the regulation of mood, emotions, and appetite. After release into the synaptic cleft, serotonin molecules either attach to the serotonin receptors (called 5-HT receptors) of the post-synaptic neuron, or they attach to receptors on the surface of the presynaptic neuron that produced the serotonin molecules, for reuptake. Reuptake is a form of recycling because the neuron takes back the released neurotransmitter for later use. Medicines called selective serotonin reuptake inhibitors (SSRIs) block the reuptake of the neurotransmitter serotonin. This blocking action increases the amount of serotonin in the synaptic cleft, which prolongs the effect of the serotonin on the postsynaptic neuron. Some scientists hypothesize that decreased levels of serotonin in the brain are linked to clinical depression and other mental illnesses. So SSRI medications such as sertraline and fluoxetine are often prescribed for depression and anxiety disorders.

Another way that a neurotransmitter is removed from a synapse is digestion by an enzyme. At cholinergic synapses (where acetylcholine is the neurotransmitter), the enzyme acetylcholinesterase breaks down the acetylcholine.

Neurotransmitters and Disease

Diseases that affect nerve communication can have serious consequences. A person with Parkinson's disease has a deficiency of the neurotransmitter dopamine. Progressive death of brain cells that produce dopamine increases this deficit, which causes tremors, and a stiff, unstable posture. L-dopa is a chemical related to dopamine that when given as a medicine, eases some of the symptoms of Parkinson's disease. The L-dopa acts as a substitute neurotransmitter, but it cannot reverse the disease.

The soil bacterium *Clostridium tetani* produces a neurotoxin that causes the disease tetanus. The bacteria usually get into the body through an injury caused by an object that is contaminated with *C. tetani* spores, such as a puncture wound caused by stepping on a nail. The *C. tetani* neurotoxin blocks the release of the neurotransmitter GABA, which causes skeletal muscles to relax after contraction. When the release of GABA is blocked, the muscle tissue does not relax and remains contracted. Tetanus can be fatal when it affects the muscles used in breathing. Thankfully, tetanus is treatable and can be prevented by vaccination.

Another bacterium called *Clostridium botulinum* produces a toxin that is occasionally found in preserved foods that have been improperly sterilized. The toxin causes a disease called botulism. Botulin toxin blocks the release of the excitatory neurotransmitter acetylcholine. Blockage of acetylcholine causes the progressive relaxation of muscles because they are unable to contract. Paralysis of the muscles used for breathing can be fatal unless the patient is treated with a respirator.

Synapses and Recent Research

Recent studies have found that electrical synapses are more common in the central nervous system than were previously thought. An electrical synapse is a link between two neighboring neurons that is formed at a narrow gap between the pre- and postsynaptic cells called a **gap junction**. At gap junctions, cells are about 3.5 nm from each other, a much shorter distance than the 20 to 40 nm distance that separates cells at chemical synapses.

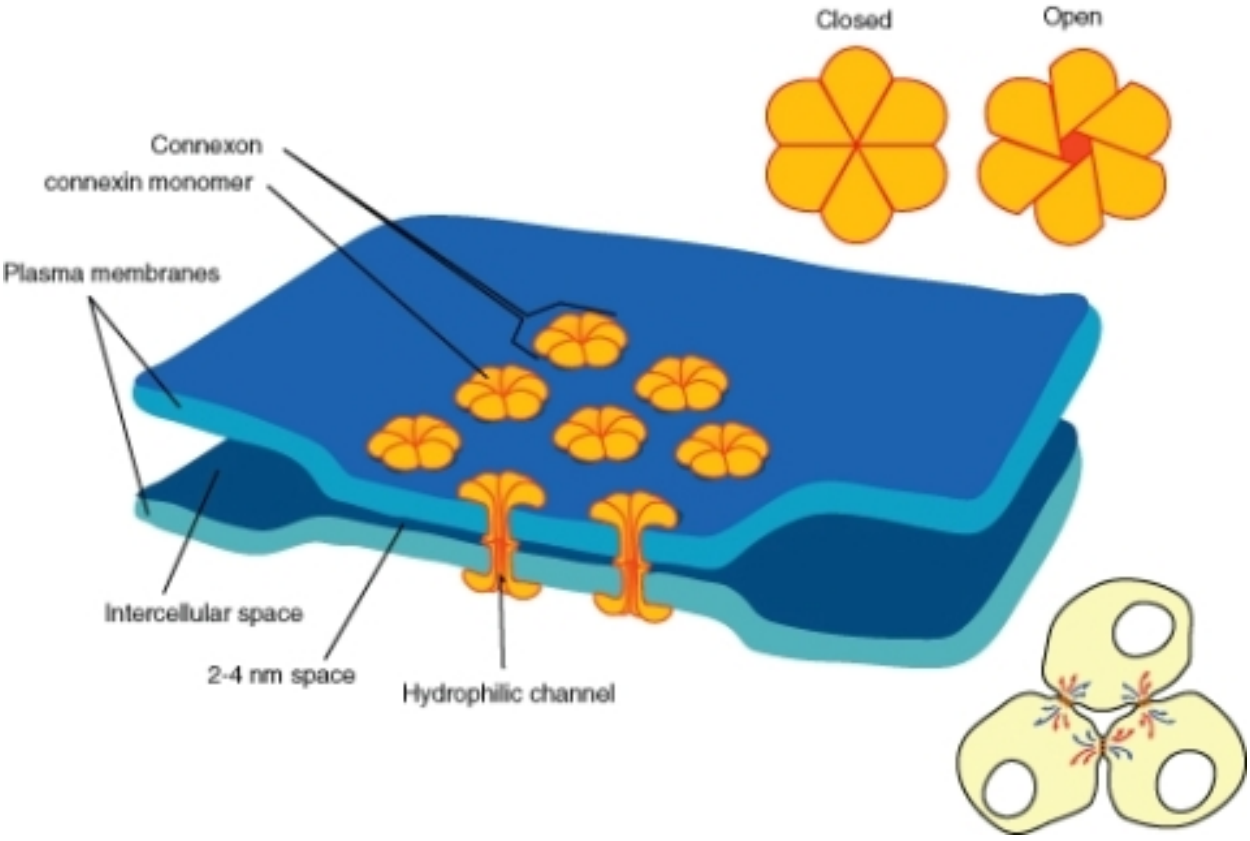

Figure 20.11: Electrical synapses. Electrical synapses are more common in the nervous system than was once thought. Cell signaling at electrical synapses is much faster than signaling at chemical synapses. The image at the bottom left of the figure shows the location of gap junctions between cells.

Each gap junction has many channels which cross the plasma membranes of both cells, as is shown in **Figure** 20.11. Gap junction channels are wide enough to allow ions and even medium sized molecules like signaling molecules to flow from one cell to the next. For example, when positive ions move through the channel into the next cell, the extra positive charges depolarize the postsynaptic cell.

Signaling at electrical synapses is faster than the chemical signaling that occurs across chemical synapses. Ions directly depolarize the cell without the need for receptors to recognize

chemical messengers, which occurs at chemical synapses. Such fast communication between neurons may indicate that in some parts of the brain large groups of neurons can work as a single unit to process information. Electrical synapses are numerous in the retina and cerebral cortex.

In addition to neurons, glial cells are an important part of the nervous system. The word *glia* means "glue" in Greek. Glial cells can be thought of as partners to neurons by aiding in the maintenance of homeostasis, signal transduction, formation of myelin and providing support and nutrition. The importance of neurons as the conductive cells of the nervous system, known as the neuron doctrine, has been questioned by recent research. The role of glial cells in processing neural information has begun to be appreciated more. There are far more glial cells than neurons, it has been estimated that glial cells outnumber neurons by as many as 50:1.

Central Nervous System

The central nervous system (CNS), which includes the brain and the spinal cord, shown in **Figure** 20.12, represents the largest part of the nervous system. The brain is the central control of the nervous system. The spinal cord carries nerve impulses from the brain to the body and from the body to the brain. Together with the peripheral nervous system (PNS), which includes all nervous tissue outside of the central nervous system, it controls virtually every activity in the body. The brain is protected by the skull and the spinal cord is protected by the vertebrae. An overview of the CNS can be viewed at http://vimeo.com/2024719.

The Brain

The brain is the most complex organ in the body. The brain contains about 100 billion neurons each of which can be connected to tens of thousands of other neurons within the brain. The brain is the source of what makes us human; the conscious mind. The mind is the set of cognitive processes related to perception, interpretation, imagination, memories, and language. Beyond cognitive functions, the brain regulates processes related to homeostasis such as respiration and heartbeat. An average adult human brain weighs between 1 and 1.5 kg (3 lb). An adult brain uses about 20-25% of the total energy used by the body, while the developing brain of an infant consumes around 60% of total energy used by the body.

The brain can be classified by the processes its different parts control. The **cerebrum** generally controls conscious functions such as problem-solving and speech, while the midbrain and the brain stem are more involved with unconscious (autonomic) functions such as breathing, heartbeat, and temperature regulation. The cerebellum is involved in coordination and control of body movement. For a video of "Brain Basics," see http://www.teachers.tv/video/13838.

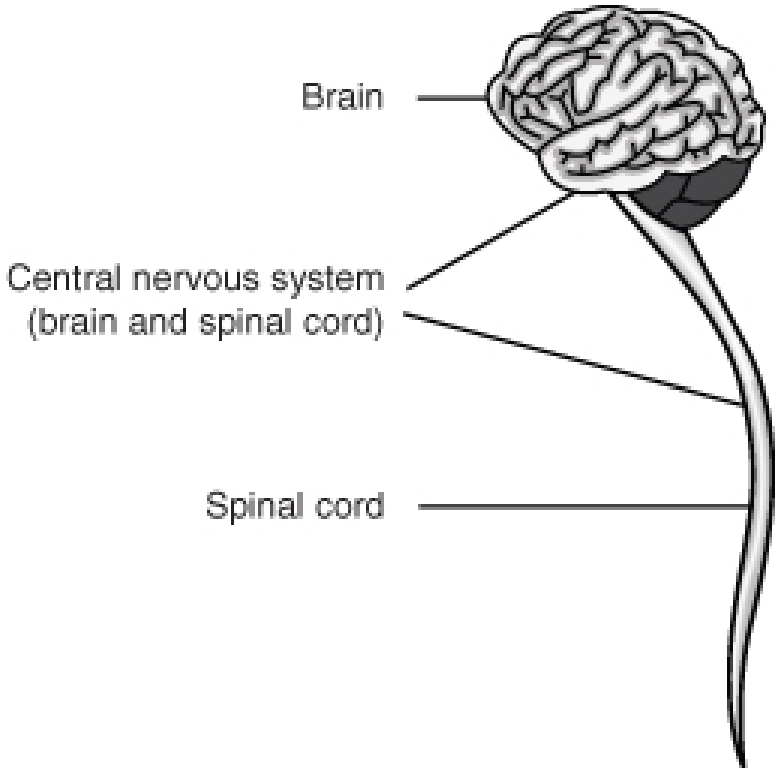

Figure 20.12: The components of the central nervous system (CNS).

Cerebrum

The cerebrum is what most people would think of as the "brain." The cerebrum lies on top of the brainstem. It is made up of two cerebral hemispheres, which are shown in **Figure** 20.13. The two cerebral hemispheres are connected to each other at the corpus callosum, the light-colored X-shaped structure in the center of the image. The corpus callosum is a wide, flat bundle of axons found deep inside the brain. Mammals (including humans), have the largest and most well-developed cerebrum among all species.

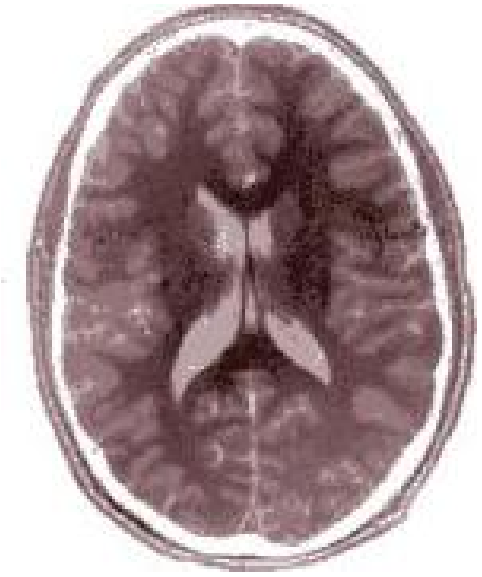

Figure 20.13: A magnetic resonance image (MRI) of the human brain in which the two hemispheres of the cerebrum can be seen.

Each hemisphere of the cerebrum can be divided into four parts, or lobes. These are: the frontal lobe, the parietal lobe, the temporal lobe, and occipital lobe. Researchers have identified a number of functional areas within each lobe, some of which are listed in **Table** 20.2. Both hemispheres look identical, but there are functional differences between them. For example, there are differences between the centers of function for spatial awareness between right and left-handed people. Each cerebral hemisphere receives sensory information and controls muscle movements of the opposite side of the body. The right hemisphere controls the left side of the body, and the left hemisphere controls the right side of the body.

Table 20.2: **Functions Controlled by the Cerebral Lobes**

Lobe	Functions
Frontal	Speech, intellectual function (reasoning, abstract thought), touch
Parietal	Speech, taste, reading

Table 20.2: (continued)

Lobe	Functions
Temporal	Hearing, smell
Occipital	Vision

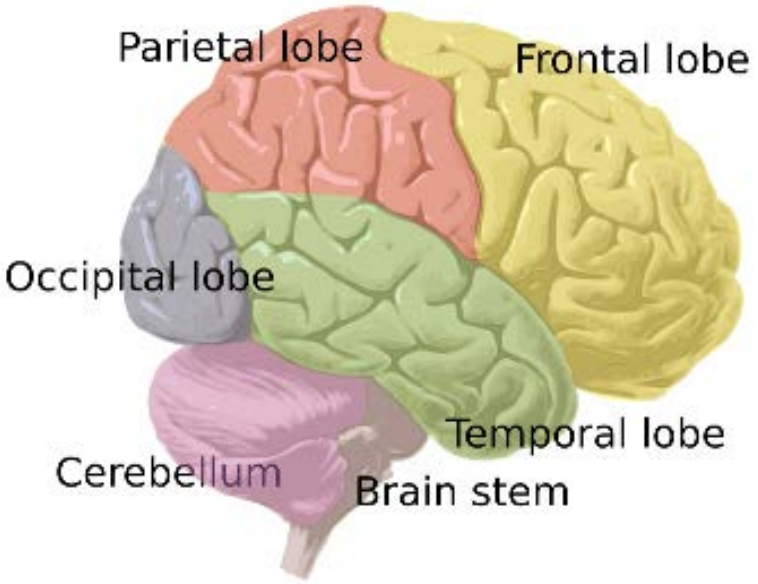

Figure 20.14: The lobes of the cerebral cortex-frontal, temporal, occipital, and parietal. The cerebellum (purple) and brain stem (gray) are not part of the hindbrain. In vertebrates, a gross division into three major parts is used.

The **cerebral cortex** is the highly-folded outer layer of the cerebrum that is between 2 mm and 4 mm thick. The lobes that make up the cerebral cortex, shown in **Figure** 20.14, are named after the skull bones that cover those areas of the brain. The many folds in the cortex allow for the large surface area of the brain to fit inside the skull. The cerebral cortex controls higher functions, such as consciousness, reasoning, emotions, and language. It also controls sensory functions such as touch, taste, smell, and responses to external stimuli. In the cerebrum, and found below the cerebral cortex, is the white matter. White matter is made up of myelinated axons that act as "cables" that link up certain parts of the right and left hemispheres.

Diencephalon

The **diencephalon** is the region of the brain that includes structures such as the thalamus, the hypothalamus, and a portion of the pituitary gland. The thalamus is believed to "translate" sensory signals for the cerebral cortex. The thalamus also plays an important role in regulating states of sleep and wakefulness. The hypothalamus gland controls certain metabolic processes and other autonomic activities such as body temperature, hunger, thirst, and circadian cycles. The hypothalamus also makes and releases neurotransmitters that control the action of the pituitary gland. The thalamus, hypothalamus, and hippocampus together are considered part of a set of structures called the limbic system. The limbic system is considered the "emotional center" of the brain.

Brain Stem

Sometimes called the "lower brain," the **brain stem** is the lower part of the brain that is joined to the spinal cord. There are three parts to the brainstem: the midbrain, the pons, and the medulla oblongata, shown in Figure 15. The midbrain is more involved with unconscious, autonomic functions. The **midbrain** deals with several types of sensory information including sound and sight. It also "translates" sensory information to be sent to the forebrain. The brainstem also helps coordinate large body movements such as walking and running. The pons relays messages to different parts of the brain (the cerebrum and cerebellum), and helps regulate breathing. Some researchers propose that it has a role in dreaming. The medulla oblongata, also called the medulla, shares some of the function of the pons. It controls several homeostatic functions that you are usually unaware of, such as breathing, heart and blood vessel activity, swallowing, and digestion.

One of the brain stem's most important roles is that of an "information highway." That is, all of the information coming from the body to the brain (sensory) and the information from the cerebrum to the body (motor) go through the brain stem. Sensory pathways for such things as pain, temperature, touch, and pressure sensation go upward to the cerebrum, and motor pathways for movement and other body processes go downward to the spinal cord. Most of the axons in the motor pathway cross from one side of the CNS to the other as they pass through the medulla oblongata. As a result, the right side of the brain controls much of the movement in the left side of the body, and the left side of the brain controls much of the movement in the right side of the body.

Cerebellum

The **cerebellum** is found just below the occipital lobe of the cerebrum. It plays an important role in coordination and the control of body movements. Many nerve pathways link the cerebellum with motor neurons, which are neurons that send information to the muscles causing them to move, and a group of nerves that provides information on the position of

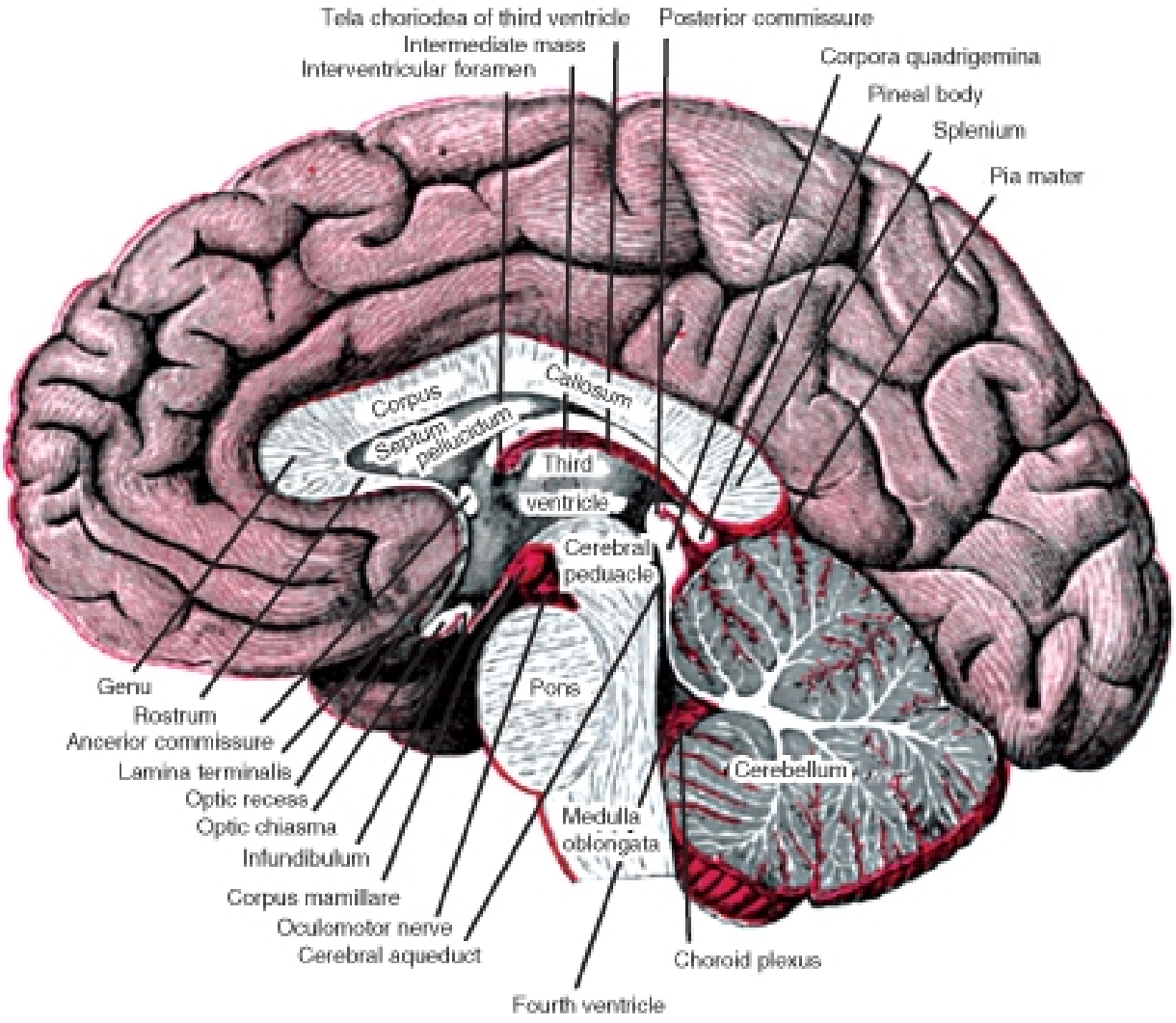

Figure 20.15: The locations of the brainstem and cerebellum. The brainstem is in the center of this image. It is made up of the pons, medulla oblongata, and the midbrain. The cerebellum is the red structure to the right of the brainstem.

the body in space. The cerebellum processes information from both these pathways, and uses the feedback on body position to fine-tune body movements. Hand-eye coordination is an example of such a function. If the cerebellum is damaged, there will not be paralysis, but the fine movement of the body (such as hand-eye coordination), balance, posture, and the ability to learn new motor skills will be negatively affected. The cerebellum is the purple structure in **Figure** 20.14. A section of the cerebellum is shown in **Figure** 20.15.

Spinal Cord

The **spinal cord** is a thin, tubular bundle of nervous tissue that extends from the medulla oblongata and continues to the lower back, where it ends in a group of fibrous extensions. It is protected by the spinal vertebrae. The main function of the spinal cord is as an information superhighway that links the sensory messages from the body to the brain. The outer cortex of the cord contains white matter (myelinated sensory and motor neurons). The central region, the grey matter, is made up of unmyelinated neurons. A cross section of the spinal cord is shown in **Figure** 20.16.

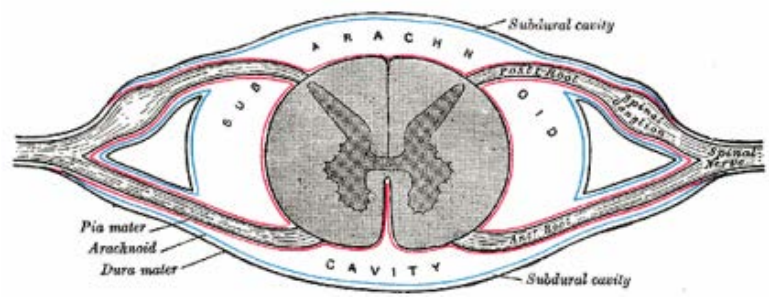

Figure 20.16: A cross section of the spinal cord. The central butterfly-shaped area is the gray matter and the area that surrounds it is the outer cortex (made up of white matter). Instructions go to the body's muscles and other areas through the motor neurons that leave the spinal cord in the spinal nerves. Sensory information from the body enters the spinal cord through sensory neurons.

Peripheral Nervous System

The peripheral nervous system (PNS) consists of the nervous tissue that lies outside the central nervous system, shown in **Figure** 20.17. The nervous tissue of the peripheral nervous system serves the limbs and organs. The central nervous system interacts with the peripheral nervous system through twelve pairs of cranial nerves that connect the brain to areas of the head and neck and 31 pairs of spinal nerves that connect the spinal cord (and CNS) to the rest of the body, such as the internal organs, arms, and legs. A **nerve** is an enclosed,

cable-like bundle of axons. Unlike the central nervous system, the peripheral nervous system is not protected by bone, making it more vulnerable to toxins and injuries.

Spinal nerves originate from the spinal cord. They control functions of the rest of the body. Each spinal nerve has a dorsal root and a ventral root, which are shown in **Figure** 20.18. The **dorsal root** is the "nerve highway" that carries sensory information from sensory receptors in the body to the CNS. The **ventral root** contains axons of motor neurons which carry information away from the CNS to the muscles and glands of the body.

These two nerve "highways" are actually parts of two subdivisions of the PNS. The **sensory division**, also known as the afferent division, carries sensory information from sensory receptors in the body to the CNS. The sensory division keeps the CNS constantly updated on events happening inside and outside the body. The **motor division**, or efferent division, carries nerve impulses from the CNS to the muscles, glands and organs of the body. The nerve impulses of the motor division cause muscles to contract and cause glands to secrete chemical signals.

Somatic and Autonomic Nervous Systems

The motor division of the peripheral nervous system is divided into the somatic nervous system and the autonomic nervous system:

The **somatic nervous system** is the part of the PNS that is associated with the conscious (voluntary) control of the body through the movement of skeletal muscles and the perception of external stimuli through senses such as touch, hearing, and sight. The system includes all the neurons connected with muscles, skin and sense organs. The somatic nervous system is made up of sensory nerves that receive sensory information from the external environment, and motor nerves responsible for muscle contraction.

Together with interneurons, the sensory and motor neurons are found in a reflex arc. A **reflex** is an automatic (involuntary) action caused by a defined stimulus and carried out through a reflex arc. For example, a person stepping on a sharp object would start the reflex action through the creation of a stimulus, (pain) within specialized pain receptors located in the skin tissue of the foot. The resulting stimulus would be passed along sensory neurons to the spinal cord. This stimulus is usually processed by an interneuron to create an immediate response to pain by initiating a motor response in the muscles of the leg which pull the foot away from the object. This reflexive action would occur as the pain sensation is arriving in the brain. A reflex arc is shown in **Figure** 20.19.

The **autonomic nervous system** (**ANS**) is the part of the peripheral nervous system that maintains homeostasis in the body. Your body carries out most of these maintenance activities without your conscious control, which is why the autonomic nervous system is also called the involuntary nervous system. The ANS has far reaching effects, such as the control of heart rate, digestion, respiration rate, salivation, and perspiration. Some autonomic

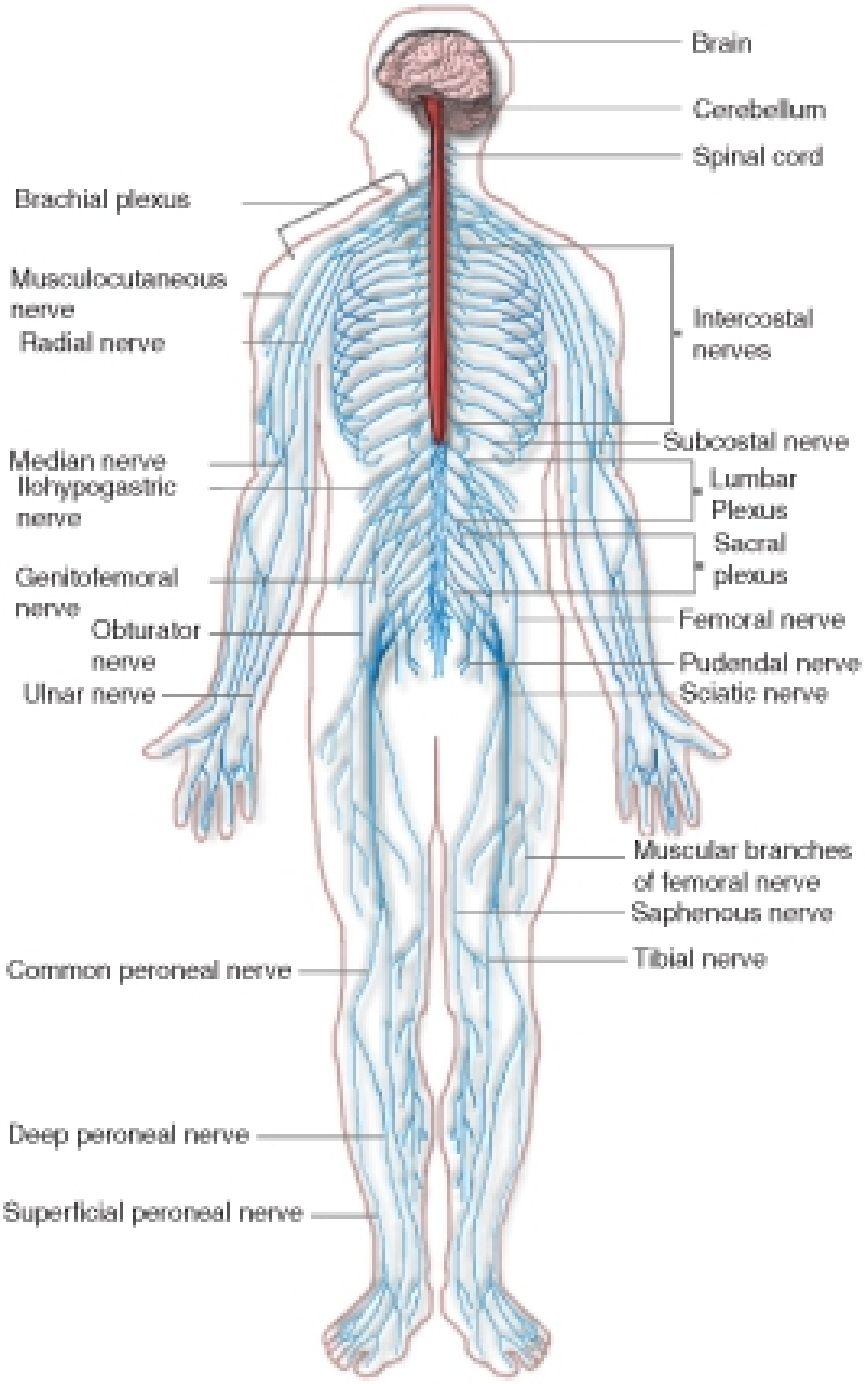

Figure 20.17: The peripheral nervous system (PNS). The peripheral nervous system extends from the CNS and reaches out to all parts of the body, from the cranial nerves found in the head to the plantar nerves in the tips of the toes.

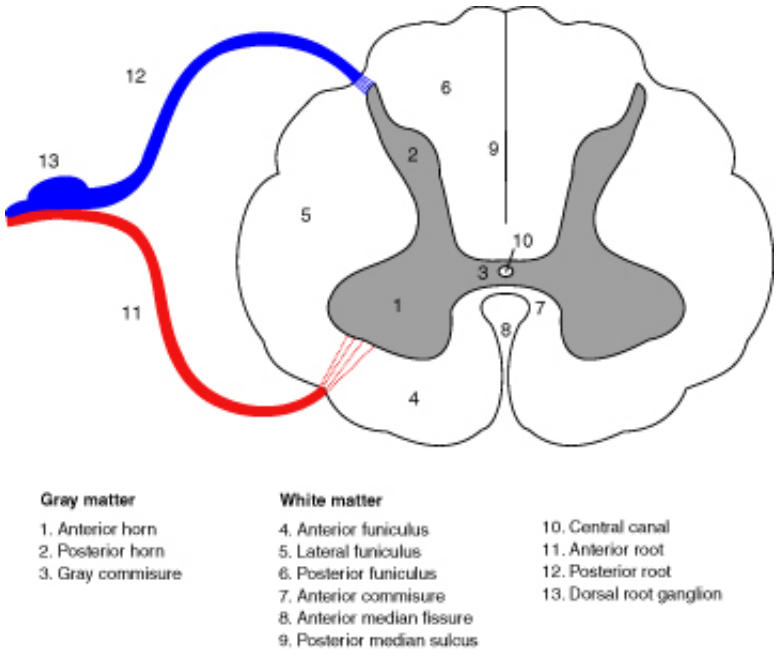

Figure 20.18: A cross section of the spinal cord. The central butterfly-shaped area (1, 2, 3) is the gray matter, the outer cortex is the white matter. Instructions going to the body's muscles and other areas go through the motor neurons that leave the spinal cord in the ventral roots (11). Sensory information from the body enters the spinal cord through sensory neurons in the dorsal roots (12). Dorsal and ventral roots occur on both sides of the spinal cord, only one side is shown in this diagram.

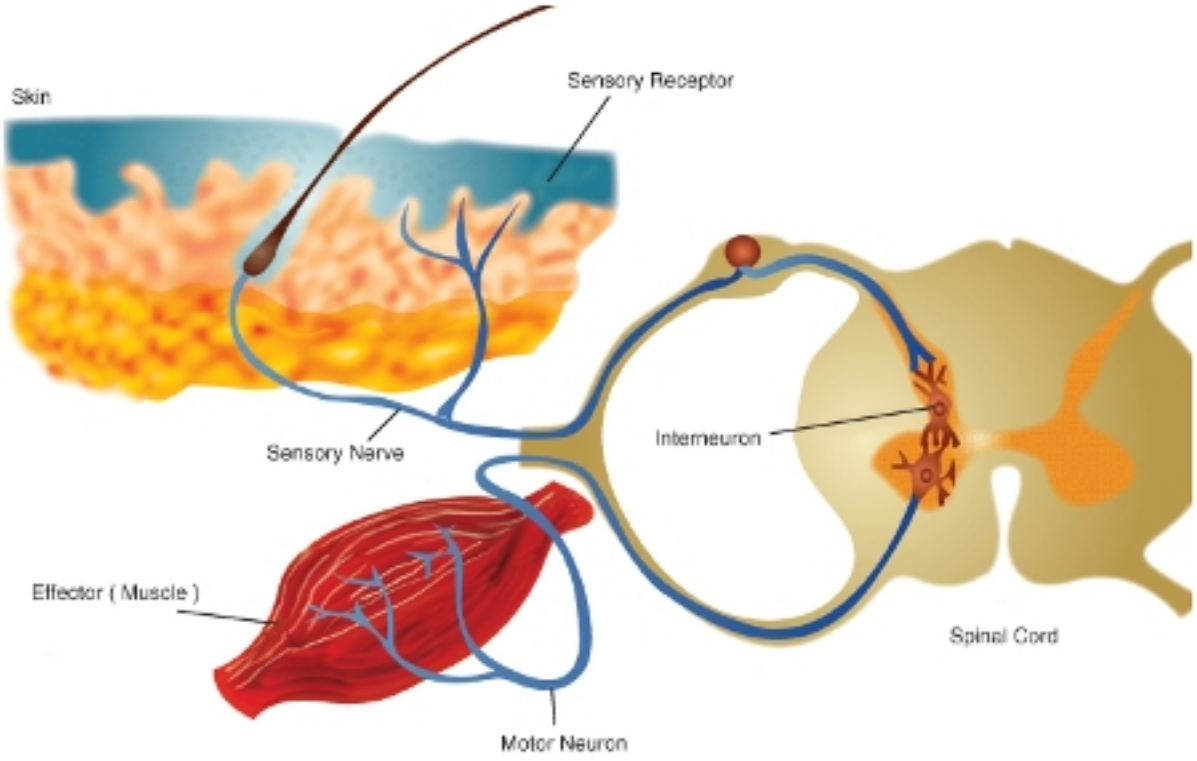

Figure 20.19: The components of a reflex. A sensory receptor that detects a stimulus and sends nerve signals to the spinal cord. These signals activate motor neurons that lead back to the effector (muscle).

nervous system functions work in line with the conscious mind, such as breathing.

The ANS is also made up of the sensory and motor neurons that send messages to and from the internal organs. These neurons form reflex arcs that pass through the medulla oblongata. This explains why even a person's cerebrum may experience trauma, yet their cardiovascular, digestive and respiratory functions will continue even if higher level functions such as awareness and consciousness, are lost. Such a low level of brain functioning is referred to as a vegetative state.

The ANS has two subdivisions: the sympathetic division and parasympathetic division. The **sympathetic division** generally stimulates body systems during emergency situations. It gets the body ready for "fight or flight," which would probably be required by the situation shown in **Figure** 20.20, while the **parasympathetic division** controls non-emergency functions such as digestion. The relationship between the divisions of the nervous system is illustrated in **Figure** 20.21.

Figure 20.20: Watch out! A situation in which your sympathetic nervous system (and hopefully your somatic nervous system), would be firing at full speed.

Sense Organs and Sensory Perception

Your senses are your body's means of making sense of the information your nervous system receives from inside your body and from the outside world. Your senses enable you to adapt to change in your environment and survive. The sensory division of the peripheral nervous system is organized into highly developed **sense organs**, which are groups of tissues that work together in responding to a specific kind of physical stimulus, such as the stimulus in **Figure** 20.22. The sense organs correspond to a defined region (or group of regions) within the brain where the nerve signals are received and interpreted. Your sense organs include

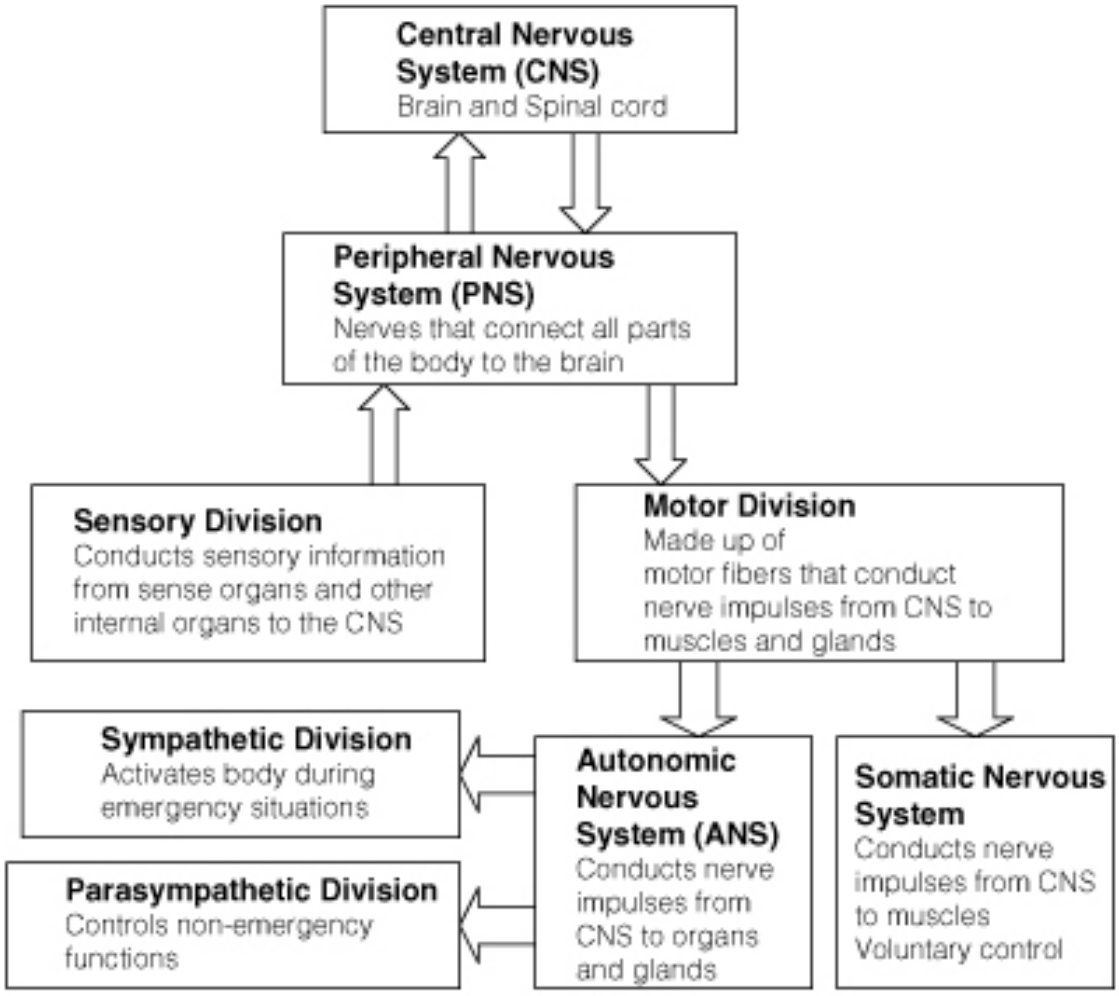

Figure 20.21: Levels of Organization of the Nervous System.

your eyes, ears, nose, mouth, and skin. They all have sensory receptors that are specific for certain stimuli. For example, the nose has sensory receptors for odors (smells). Sensory neurons send nerve impulses from sensory receptors to the central nervous system. The brain then interprets the nerve impulses to form a response.

Figure 20.22: Can you smell these fresh, juicy oranges and kumquats? Your senses of smell, taste and sight are also important in developing an appetite. Just think of how appetizing these fruits would be if they were blue, crunchy, and smelled like burned toast.

A sensory receptor is a cell, or a group of cells that detect stimuli. Sensory receptors can be classified based on the type of stimuli to which they respond.

- **Chemoreceptors** respond to chemical stimuli.
- **Mechanoreceptors** respond to mechanical stress or strain (movement).
- **Thermoreceptors** respond to temperature changes.
- **Photoreceptors** respond to variations in light.
- **Baroreceptors** respond to pressure.

Specific areas of the brain interpret information from each sense organ. For example, regions of the occipital lobe interpret nerve impulses that come from the sensory receptors of the eyes, and regions of the temporal lobe interpret sensory information from the ears through the nerves that enter the brain in these areas, as shown in **Figure** 20.23. It is generally agreed that there are at least seven different senses in humans. These are sight, sound, taste, smell, touch, balance, and body awareness (the sense of knowing where the regions of your body are located at any one time). At least two other senses that humans do not have are observed in other organisms. Examples include electroreception, the ability to detect electric fields, and magnetoreception, the ability to detect magnetic fields.

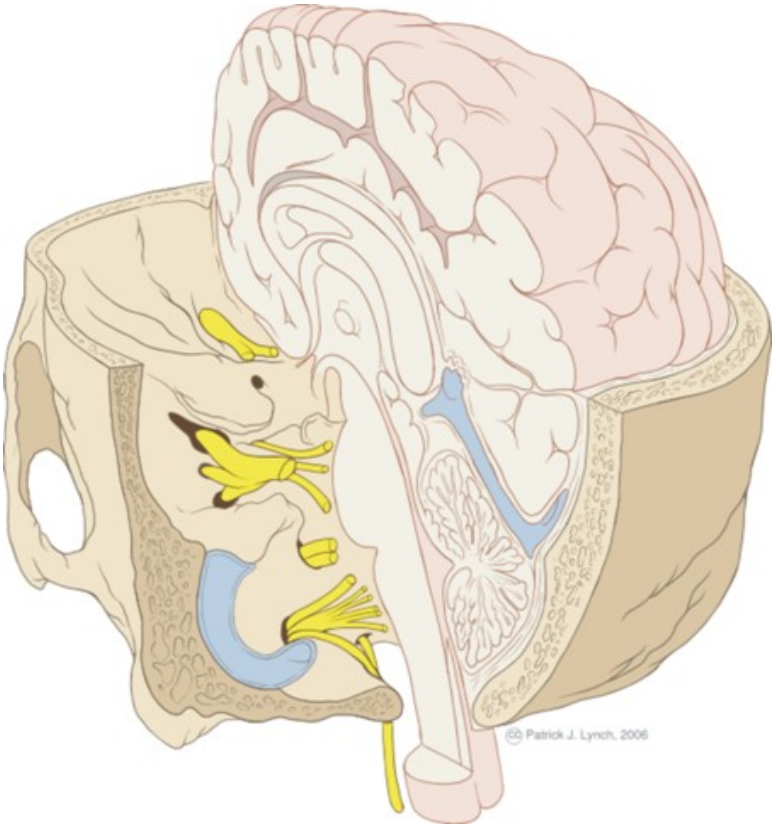

Figure 20.23: The entry of sensory nerves into the brain. Among other nerves, the sensory nerves for smell, sight, hearing, and taste (yellow structures) can be seen entering the skull. You can also see how the cerebrum, thalamus, cerebellum, and brain stem are nested within the skull.

Sight

Sight or vision describes the ability of the brain and eye to detect certain wavelengths of electromagnetic radiation (light), and interpret the image as "sight." Different receptors are responsible for the perception of color (the frequency of photons of light) and perception of brightness (number of photons of light). Photoreceptors are found in the retina, shown in **Figure** 20.24.

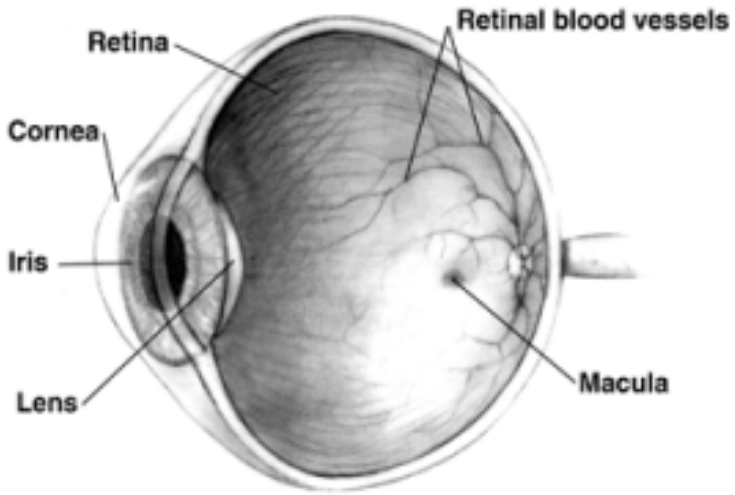

Figure 20.24: The structure of the eye. The macula is a spot near the center of the retina that has a diameter of about 1.5 mm. Near its center is the fovea, a small pit that contains the largest concentration of cone cells in the eye and is responsible for central vision. The macula is the point of sharpest vision. A video of the human eye is available at

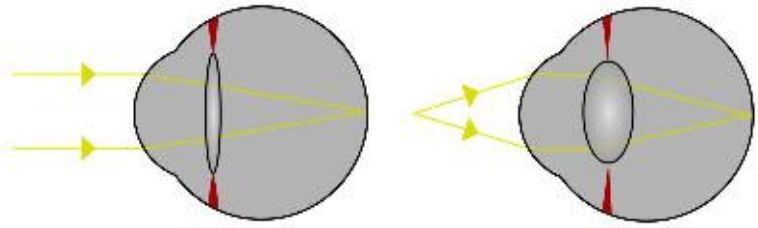

Figure 20.25: Focusing light in the retina. This diagram shows how light from a distant source is bent by the stretched lens to strike the retina, and how light from a closer source is bent even more sharply by the relaxed lens to strike the retina.

The structure of the eye owes itself completely to the task of focusing light onto the retina, the light-sensitive inner layer of the eye. First, light passes through a clear protective layer

called the **cornea**, shown in **Figure** 20.24. Light then passes through the **pupil**, which is the opening in the iris, and into the interior of the eye. After passing through the pupil, the light then travels through the lens, a transparent, biconvex structure that, along with the cornea, helps to focus light on the retina. Muscles attached to the lens change the shape of the lens to bend the light rays so that they focus on the retina, as shown in **Figure** 20.25. Light hitting the retina causes chemical changes in the photosensitive cells of the retina, the products of which trigger nerve impulses which travel to the brain along the optic nerve.

The retina has two forms of photosensitive cells important to vision—rods and cones. **Rod cells** are highly sensitive to light which allows them to respond in dim light and dark conditions, but, they cannot detect color. These are the cells which allow humans and other animals to see by moonlight, or in a dimly-lit room. This is why the darker conditions become, the less color objects seem to have. **Cone cells** respond to different wavelengths of bright light to initiate a nerve impulse. They are also responsible for the sharpness of images. Cones do not respond well in poor light conditions, which is the reason why you see things in dim light as fuzzy shades of gray.

Humans have three different types of cone cells that respond to different wavelengths of light. These cone cells contain a pigment that absorbs the energy from different wavelengths of light to initiate a nerve impulse. Activation of the visual pigments by certain wavelengths of light opens ion channels on the membrane of the cone or rod cell. This leads to an action potential that is carried by the millions of neuron axons that make up the optic nerve to the visual centers of the brain. The brain integrates the nerve impulses from the cone cells and perceives the world in all the colors of the visual spectrum. A person who is colorblind has damaged or missing cones, and is unable to perceive certain colors.

Hearing

Hearing is the sense of sound perception that results from the movement of tiny hair fibers in the inner ear. These hairs detect the motion of a membrane which vibrates in response to changes in air pressure. Sound can also be detected as vibrations that are conducted through the body. Sound wave frequencies that are too low or too high to be heard by the ear can be detected this way. Audible sound is sensed by the ear.

The folds of cartilage surrounding the outer ear canal are called the **pinna**. Sound waves are gathered by the pinna, and channeled down the **auditory canal**, a tube-shaped opening of the ear which ends at the tympanic membrane, or **eardrum**.

Sound waves traveling through the ear canal hit the eardrum and cause it to vibrate. This wave information travels across the air-filled middle ear cavity through a group of three tiny, delicate bones: the **hammer**, the **anvil**, and the **stirrup**, shown in **Figure** 20.26. This group of bones transfers the eardrum vibrations to another membrane called the oval window. The oval window separates the middle ear from the inner ear. The inner ear contains the cochlea.

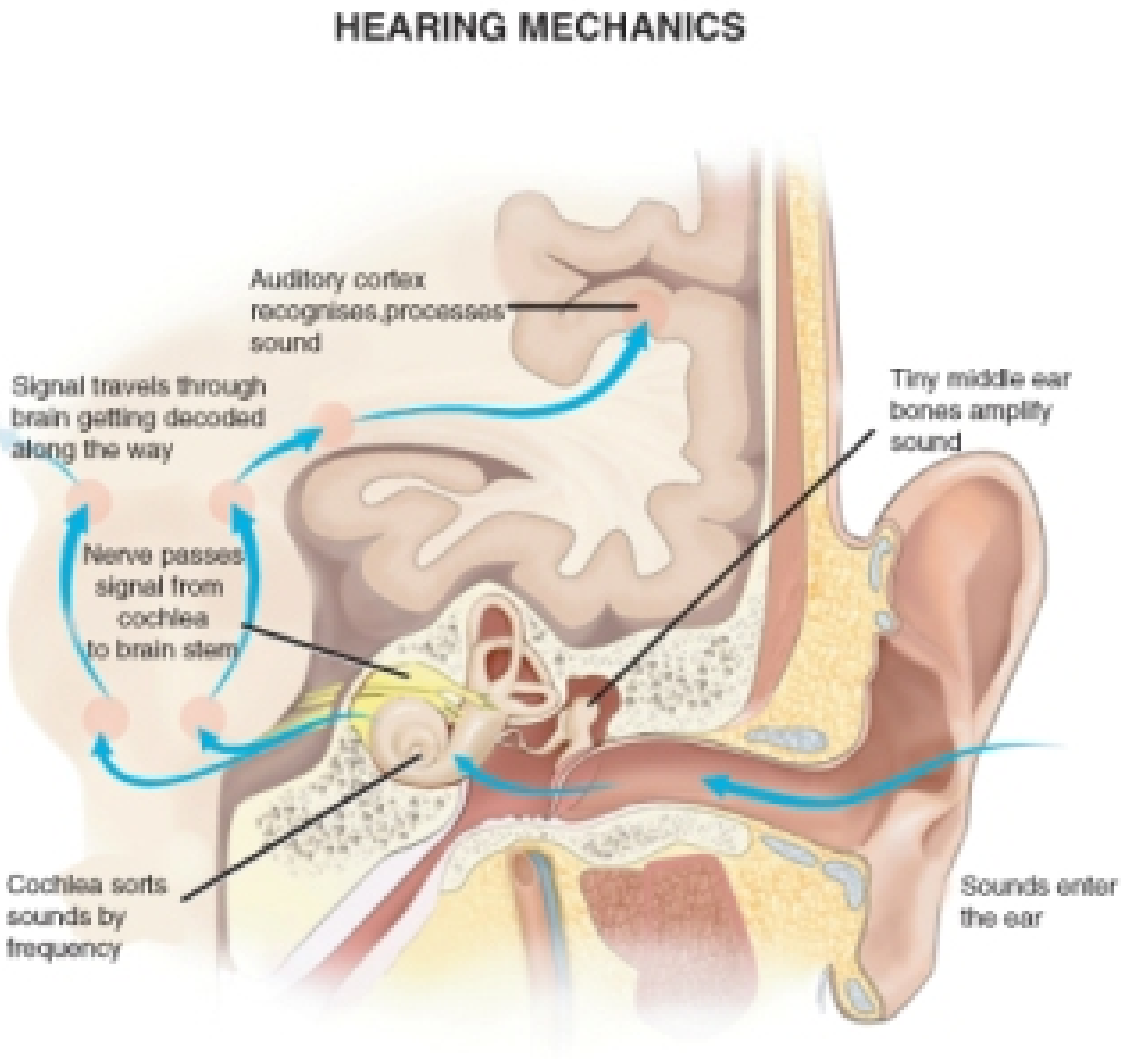

Figure 20.26: The detection of sound by your ear.

The **cochlea** is a coiled tube that is filled with a watery liquid, which moves in response to the vibrations coming from the middle ear through the oval window. As the fluid moves, thousands of mechanoreceptors called **hair cells** bend, releasing a neurotransmitter. The neurotransmitter causes an action potential in the neurons of the auditory nerve. The action potential travels along the auditory nerve to structures in the brainstem, then to the thalamus, and then to the auditory centers of the brain in the temporal lobe of the cerebral cortex.

A very strong movement of the fluid within the cochlea, caused by very loud noise, can kill hair cells. This is a common cause of partial hearing loss and is the reason why users of firearms or heavy machinery should wear earmuffs or earplugs. Destruction of the hair cells usually leads to permanent hearing loss because once destroyed, the hairs do not generally grow back.

Balance and the Ears

It might be hard to believe, but your ears are also in charge of your sense of balance! The **semicircular canals** are three fluid-filled interconnected tubes found inside each ear. They can be seen in **Figure** 20.26, directly above the cochlea. The canals are positioned at angles between 95 to 115 degrees relative to one another. The angles between the canals are not perpendicular, so movements of the head cause movement of fluid in two canals at the same time.

Each canal is filled with fluid called endolymph and motion sensors with little hairs, called cilia, line each canal. Movement of the head and body cause the endolymph in the canals to move about. The hair cells sense the strength and direction of the fluid's movement and send electrical signals to the cerebellum which interprets the information and responds to help keep the body's sense of balance. The interaction of the semicircular canals and the cerebellum allow the performer in **Figure** 20.27 to do his act.

When the sense of balance is interrupted it causes dizziness and nausea. Balance can be upset by an inner ear infection, a bad head cold or a sinus infection, or a number of other medical conditions. It can also be temporarily disturbed by rapid and repetitive movement, for example riding on a merry-go-round or spinning around in a circle.

Taste and Smell

Taste is one of the two main chemical senses, the other being smell. There are at least four types of taste receptors on the tongue. Taste stimuli from each receptor type send information to a different region of the brain. The four well-known receptors detect sweet, salt, sour, and bitter. The existence of a fifth receptor, for a sensation called umami, was confirmed in 2000. The umami receptor detects the amino acid glutamate, which causes a savory, "meaty" flavor in foods.

Figure 20.27: Good balance required! This performer's sense of balance is dependent on communication between his semicircular canals and his cerebellum.

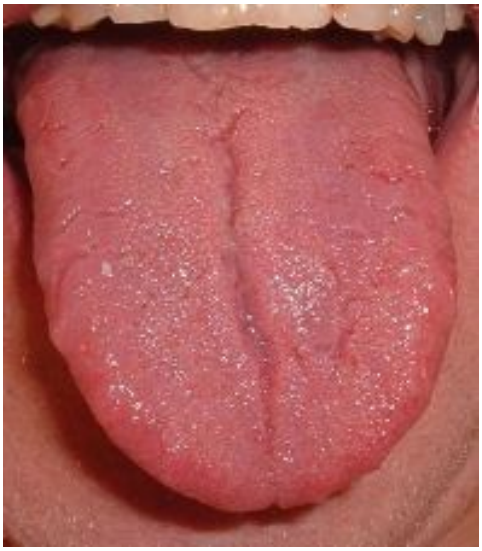

Figure 20.28: The location of taste buds. Most of the taste buds in the mouth are embedded in the papillae, the little bumps that cover the tongue. The deep groove (fissure) that runs down the center of the tongue in this photo is a common and perfectly normal condition.

The chemoreceptors of the mouth are the taste cells that are found in bundles called taste buds. Most of the taste buds are embedded within the tiny papillae or "bumps" that cover the tongue, shown in **Figure** 20.28. Each receptor has a different way of detecting certain compounds and starting an action potential which alerts the brain. The compounds bind to receptors in the taste cells and stimulate neurons in the taste buds. The action potential moves along the facial nerves to the thalamus and then to the taste center of cerebral cortex for interpretation by the brain. The tongue can also feel sensations that are not generally called tastes. These include: temperature (hot or cold), coolness (as in "minty" or "fresh"), spiciness or hotness (peppery), and fattiness (greasy).

Smell is the other "chemical" sense. The chemoreceptors of smell are called **olfactory receptors.** About 40 million olfactory receptor neurons line the nasal passages. Different odor molecules bind to and excite specific olfactory receptors. The combination of excitatory signals from different receptors makes up what we identify as "smell." Signals from the olfactory receptors travel along nerves to the olfactory bulb in the brain where they then move to the smell center in the frontal lobe of the cerebral cortex. Olfactory receptor neurons in the nose differ from most other neurons in that they die and regenerate on a regular basis. A dog's keen sense of smell is due to the large area of its nasal passages that are covered by olfactory receptors, and the large number of nerves that bring nerve impulses from the receptors to its brain. For example, the area in which olfactory receptors are located inside the human nose (called the olfactory epithelium), which is shown in **Figure** 20.29, measures about 12 cm^2. The olfactory epithelium of some dogs' noses can measure about 150 cm^2!

Have you ever noticed that you cannot taste anything when your nose is stuffed up? That

is because your senses of smell and taste are closely linked. This is due to the fact that your nasal cavity, located behind the nostrils, connects to your mouth at the back of your throat, as shown in **Figure** 20.29. Your olfactory receptors and taste receptors both contribute to the flavor of food. Your tongue can only tell among a few different types of taste, while your nose can distinguish among hundreds of smells, even if only in tiny amounts.

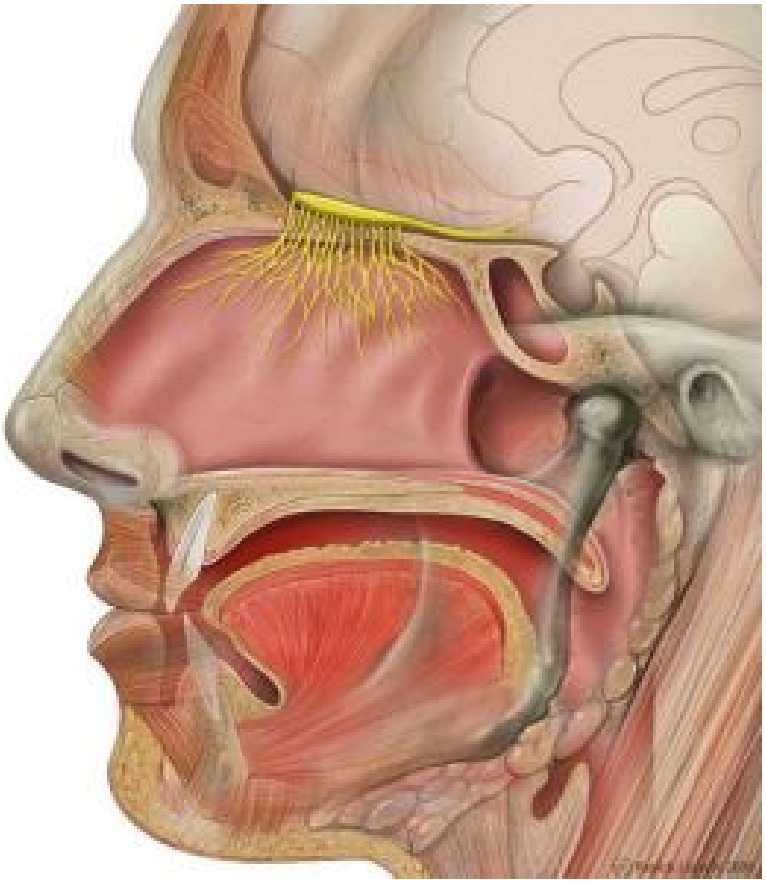

Figure 20.29: The location of olfactory nerves. Olfactory receptors and their associated nerves (yellow) line the top of the nasal passages. Nerve messages from the receptors are sent to the brain to be interpreted as certain smells.

Touch, Pressure, and Pain

Touch is the sense of pressure perception, which is generally felt in the skin. There are a variety of pressure receptors that respond to variations in pressure and tension. Mechanoreceptors are most numerous on the tongue, lips, face, palms (including fingertips), and soles of the feet.

There are several types of pain receptors, called **nociceptors**, which respond to potentially damaging stimuli. They are mostly found in the external parts of the body such as the skin,

cornea, and mucous membranes, but are also found in muscles, joints, and some internal organs. Nociceptors are classified according to the stimuli to which they respond: thermal, mechanical or chemical. But some receptors respond to many different damaging stimuli of a chemical, thermal, or mechanical nature. Thermal receptors are activated by potentially harmful heat or cold, temperatures above 45°C and below 5°C. Mechanical receptors respond to excess pressure, squeezing, or bending, the type of painful stimuli that a cactus such as the one in **Figure** 20.30 would cause. Together these nociceptors allow the organism to feel pain in response to damaging pressure, excessive heat, excessive cold and a range of chemicals, the majority of which are damaging to the tissue surrounding the nociceptor.

Figure 20.30: Mechanical pain receptors in your skin would warn you if you got too close to this prickly cactus.

Drugs and the Nervous System

A **drug** is any chemical or biological substance that affects the body's structure or functions. Drugs in the form of medicines are used to treat many illnesses and disorders. A **medicine** (or medication), is a drug that is taken to cure or reduce the symptoms of an illness. However, drugs, whether they are medicines, legal or illegal drugs, can be abused for the effects they have on the central nervous system (CNS). In fact many medical uses of drugs depend on the powerful effect they have on brain function. For example, anti-depression medicines are used to treat depression and anxiety disorders, and antipsychotic medicines are used to treat schizophrenia and bipolar disorder.

A **psychoactive drug** is a substance that affects the central nervous system by altering cognitive function. Change in cognitive function results in changes in how a person feels,

thinks, perceives, and acts. Almost everyone has used a psychoactive drug at some time in their life, and many people take such drugs daily. For example, the coffee or tea that you may have drank to waken yourself up this morning, or the cola, energy drink, or chocolate that you had as a snack contain the psychoactive drug caffeine. Caffeine is a CNS stimulant that makes you feel less drowsy and more alert. Coffee beans, the most common source of caffeine, are shown in **Figure** 20.31.

Figure 20.31: Roasted coffee beans. Coffee beans are a common source of the stimulant caffeine. Other plant sources include the leaves of tea, cocoa, yerba mate, and guarana plants. These plants use caffeine as a means of protection against being eaten. The caffeine in the leaves of these plants can paralyze and kill the insects that feed upon them.

Drugs and the Brain: How Psychoactive Drugs Work

How we perceive stimuli, feel, think, and do is a result of neurons sending action potentials and neurotransmitters to each other and to other cells in the body. Psychoactive drugs affect how neurons communicate with each other. These drug molecules can alter neurotransmission, by blocking receptor proteins, mimicking neurotransmitters, or changing the amount of neurotransmitter in the synapse, shown in **Figure** 20.32, by blocking reuptake. In this way a psychoactive drug can change how we feel, think, and interact with the world. Sometimes such effects are beneficial, such as taking a prescribed painkiller (hydrocodone, for example), to ease the pain of a broken bone. Sometimes the effects are harmful, which could happen if the person continued to take the powerful painkiller long after their broken bone had healed. Some examples of psychoactive medicines are listed in **Table** 20.3.

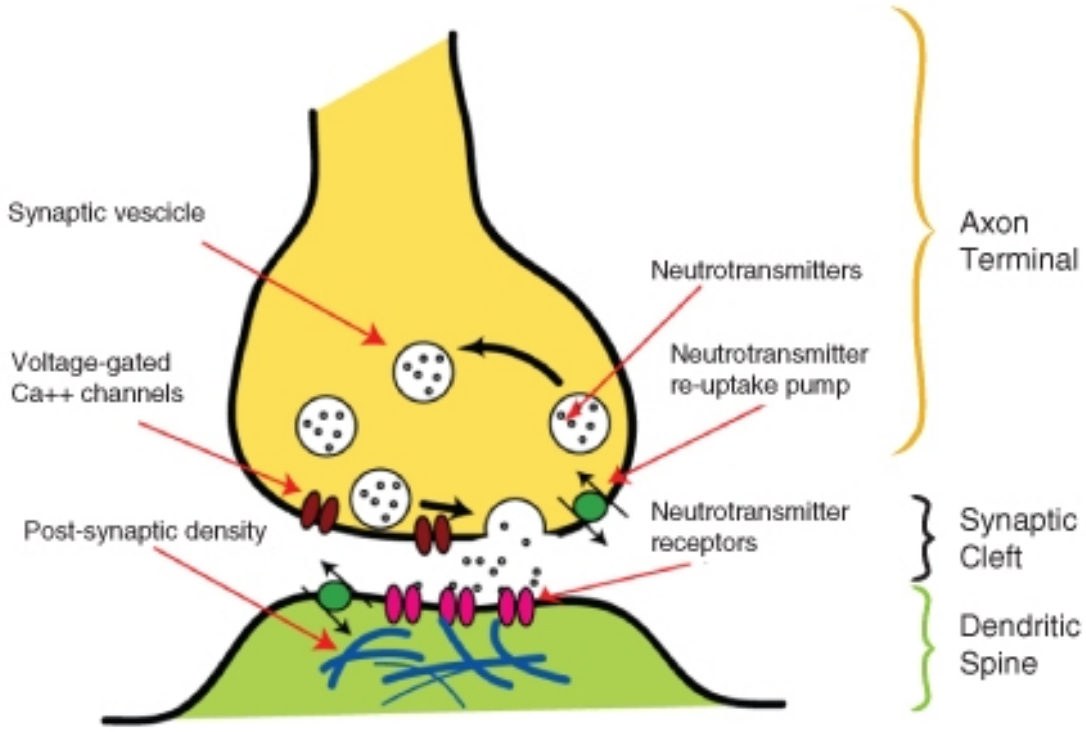

Figure 20.32: The release of neurotransmitter into the synaptic cleft. Depending on its method of action, a psychoactive substance may block the receptors on the post-synaptic neuron, or block reuptake or affect neurotransmitter synthesis in the pre-synaptic neuron.

Table 20.3: **Some Psychoactive Medicines and Their Uses**

Type	Uses	Example	Action
Anesthetics	Block pain and other sensations. Often induce unconsciousness, which allows patients to undergo medical procedures.	Lidocaine, nitrous oxide	Mimic the inhibitory neurotransmitter GABA, or increase the amount of GABA in the synapse which prevents an action potential.
Painkillers (analgesics)	Reduce the sensation of pain. Includes narcotics and non-steroidal anti-inflammatory drugs (NSAIDS)	Narcotics: morphine and codeine NSAIDS: aspirin and acetaminophen (paracetamol).	Drug molecules mimic endogenous opioids "natural painkillers," such as endorphins, by binding to opioid receptors.
Antidepressants	Antidepressants are used to treat disorders such as clinical depression, anxiety, and eating disorders	Selective Serotonin Reuptake Inhibitors (SSRIs); Monoamine oxidase inhibitors (MAOIs)	SSRIs: Block the uptake of the neurotransmitter serotonin by presynaptic neuron MAOIs: Prevent an enzyme from breaking down serotonin in the synapse. Both actions result in an increase of serotonin in the synapse.
Stimulants	Used to treat disorders such as attention deficit disorder and to suppress the appetite	Amphetamine salts	Increases extracellular levels of dopamine, norepinephrine and serotonin by various means

Table 20.3: (continued)

Type	Uses	Example	Action
Antipsychotics	Used to treat psychoses such as schizophrenia and mania.	Chlorpromazine	Blocks dopamine receptors in post synaptic neurons
Cough medicines (antitussives)	Used to treat persistent coughing.	Dextromethorphan (DXM) and codeine	Inhibit the action of, the NMDA receptor in the post synaptic cell. Reduces action potential, similar in action to anesthetics

Drug Abuse

Psychoactive drugs bring about changes in mood and feelings that a user may find desirable, therefore many psychoactive substances are abused. **Drug abuse** is the repeated use of a drug without advice or guidance of a medical professional, and use for reasons other than for what the drug was originally intended. With continued use of a drug, a person might find that they cannot function normally without the drug, a state called **physical dependence**. However, note that physical dependence is not in itself bad, for example, a person who has diabetes is physically dependent on insulin injections. Their body cannot work properly without it. Emotionally or mentally needing a drug to be able to function normally is called **psychological dependence**. When a person continues to take a psychoactive drug, they eventually need to take larger doses of the drug to get the desired effect; this process is known as building a **tolerance** to the drug. Drug tolerance can involve both psychological and physical factors.

A person who is abusing a drug may eventually lose control of their drug-taking behavior, partly due to the changes the drug has caused in their brain, and partly due to learned drug-abuse behaviors (such as stealing and lying to get money or drugs). In the state of **addiction**, a drug addict's life and activities revolve around getting more of the drug to feed their habit, even if it leads to severe consequences such as getting arrested, dropping out of school, or isolation from friends and family. In a person who is addicted to a drug, the pattern of increasing dose due to tolerance can lead to a **drug overdose**, also known as an OD. A drug overdose is generally considered harmful and may lead to death. Drug dependence and addiction are caused by changes in the way neurons in the CNS send and receive neurotransmitters. It is for this reason dependency and addiction are treated as brain disorders by medical professionals.

Several classes of psychoactive drugs are commonly abused. **Stimulants** such as cocaine,

nicotine, and amphetamine increase the activity of the sympathetic nervous system, the central nervous system, or both. Stimulants generally increase heart rate, blood pressure, and increase the sense of alertness. Some stimulants, such as caffeine, are used medicinally to increase or maintain alertness, and to counteract fatigue. High doses of stimulants can be fatal. A common source of nicotine is cigarette tobacco, shown in **Figure** 20.33.

Figure 20.33: Cigarettes are a common source of nicotine. Nicotine is a compound that is found in the leaves of the tobacco plant. It is a potent neurotoxin for insects, and was once used as an insecticide. In addition to the addictive nature of nicotine, long-term tobacco use carries significant risks of developing various cancers as well as strokes and severe cardiovascular and respiratory diseases.

Hypnotics, also known as **depressants**, such as alcohol, codeine, barbiturates, and benzodiazepines generally decrease the activity of the central nervous system. Depressants slow down brain function and give a drowsy or calm feeling. However, taking too much of a depressant drug can cause dangerously slow breathing and heart rates, and may result in death. Many depressants acting on the CNS do so by increasing the activity of the inhibitory neurotransmitter gamma-aminobutyric acid (GABA), although there are many receptors that are affected by different depressants. GABA calms the activity of the CNS and promotes sleep. Drugs that stimulate the activity of this amino acid slow down brain function and cause a drowsy or calm feeling, so depressants are generally prescribed to relieve symptoms of anxiety or insomnia.

Hallucinogens, also known as psychedelic drugs, such as lysergic acid diethylamide (LSD), phencyclidine (PCP), and ketamine, are psychoactive drugs that do not increase or decrease a certain feeling or emotion, but rather they induce experiences, such as sensory distortions

and "out-of-body experiences," that are very different from those of ordinary consciousness. These experiences are often called trance-like states. The use of psychedelic drugs has been linked to a potential for brain damage.

There are many ways in which psychoactive drugs can affect the CNS. Each drug has a specific action on one or more neurotransmitters or receptors. Drugs that increase activity in particular neurotransmitter systems are called **agonists**. They act by increasing the synthesis of one or more neurotransmitters or reducing its reuptake from the synapses. Drugs that reduce neurotransmitter activity are called **antagonists**, and work by interfering with synthesis or blocking postsynaptic receptors so that neurotransmitters cannot bind to them. The drug ketamine, which is used as an anesthetic and a painkiller, blocks the action of the neurotransmitter glutamate. Diacetylmorphine (heroin) enhances the action of endorphins in the brain. Different drugs also affect different parts of the brain. For example, drugs that affect breathing, such as cough suppressants, affect the brainstem to stop the coughing reflex. Painkillers (analgesics) block pain messages coming through the spinal cord from the body. In **Figure** 20.34 the brainstem region is blue, and the spinal cord is yellow.

How Addiction Happens

The **neurobiological theory of addiction** proposes that certain chemical pathways are greatly changed in the brain of an addicted person. Almost all drugs that are abused affect a certain set of brain structures in the limbic system called the "brain reward system," shown in **Figure** 20.27. The neurotransmitter dopamine is commonly associated with the brain reward system. The system providing feelings of pleasure (the "reward"), that motivates a person to perform certain activities over and over again. Dopamine is released at synapses by neurons when a person has a pleasurable experience such as eating a favorite food, or eating when very hungry. Such mechanisms have evolved to ensure the survival of organisms.

Some drugs, such as cocaine, nicotine, amphetamines, and alcohol directly or indirectly increase the amount of dopamine in the limbic structures. The pleasurable feelings that these drugs produce trick the body into thinking that the drug is good,important for survival, and needs to be taken repeatedly. Drugs that directly affect the brain reward system are highly addictive. The stimulant nicotine, which is found in tobacco, is highly addictive.

Cocaine is an example of a psychoactive drug that is both used as a medicine, and abused as a drug. Cocaine is highly addictive. It is a dopamine transporter blocker—it blocks the reuptake of dopamine by the presynaptic neuron. This action increases the amount of dopamine left in the synaptic cleft, so dopamine has a stronger effect on the postsynaptic neuron. Continued cocaine use causes a reduction in the number of dopamine receptors on the postsynaptic neuron. Eventually, the post synaptic neuron becomes understimulated because there are fewer dopamine receptors on it to respond to dopamine. At this point, more cocaine must be taken to stimulate the postsynaptic neuron into an action potential. If a person becomes dependent on the drug, they need cocaine for their body to act normally.

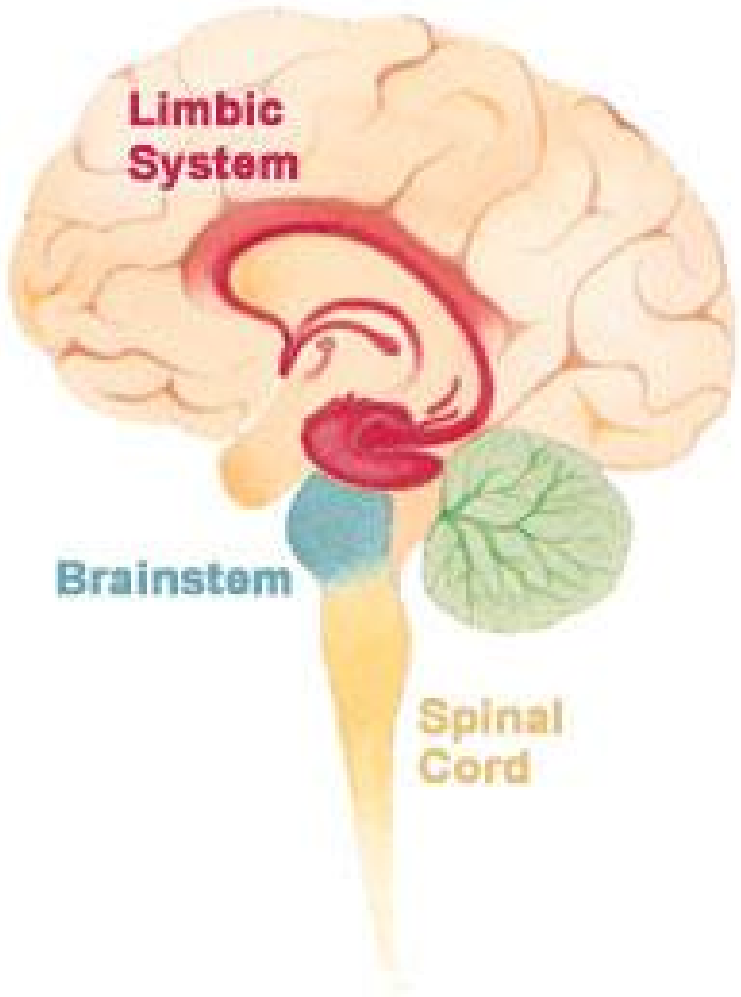

Figure 20.34: The limbic system (in red) includes structures in the human brain that have been linked to emotion, motivation, and emotional association with memory. The action of neurotransmitters in the limbic system is altered by addictive drugs.

If a person were to stop taking the drug at this point, their body would not be able to act normally, and they would experience a range of uncomfortable and painful symptoms called **withdrawal**. Symptoms of withdrawal include vomiting, diarrhea, and depression.

Many psychoactive substances are used or abused for their mood and perception altering effects, including those with accepted uses in medicine and psychiatry. Classes of drugs that are frequently abused include some of the drugs listed in **Table** 20.4. Drugs that are deemed by to have no medical uses and a high potential for abuse are usually illegal.

Not all drugs are physically addictive, but any activity that stimulates the brain reward system can lead to psychological addiction. Drugs that are most likely to cause addiction are drugs that directly stimulate the dopaminergic system, like cocaine, nicotine, and amphetamines. Drugs that only indirectly stimulate the dopaminergic system, such as psychedelics, are not as likely to be addictive.

Table 20.4: **Some Common Drugs of Abuse**

Psychoactive Drugs	Effects	Examples	Some Common Forms or Names
Stimulants	Elevate the central nervous system and raise level of alertness and wakefulness	Caffeine, cocaine, amphetamine, methamphetamine	Coffee, coke, meth, ecstasy (X)
Hallucinogens	Induce perceptual and cognitive distortions	LSD, psilocybin, mescaline, PCP	Acid, magic mushrooms, peyote, angel dust
Hypnotics	Depress the CNS, and induce sleep	Barbiturates, opioids (e.g. codeine, morphine, oxycodone), benzodiazepines, ethanol	Diazapam, alcohol
Analgesics	Induce euphoria, reduce sensation of pain	Codeine, morphine, ketamine, heroin, phencyclidine (PCP), tetrahydrocannabinol (THC)	Horse, angel dust, cannabis, marijuana

Lesson Summary

- Neurons are typically made up of a cell body, dendrites, and an axon. The cell body contains the nucleus and other organelles similar to other body cells. The dendrites extend from the cell body and receive a nerve impulse from another cell. The cell body

collects information from the dendrites and passes it along to the axon. The axon is a long, membrane-bound extension of the cell body that passes the nerve impulse onto the next cell.

- Voltage is electrical potential energy that is caused by a separation of opposite charges across the membrane. The voltage across a membrane is called membrane potential. Membrane potential is the basis for the conduction of nerve impulses along the cell membrane. In an action potential, the cell membrane potential changes quickly from negative to positive as sodium ions flow into and potassium ions flow out of the cell through ion channels.
- A neurotransmitter is a chemical message that is used to relay electrical signals between a neuron and another cell. Neurotransmitter molecules are made inside the presynaptic neuron and stored in vesicles at the axon terminal.
- The central nervous system represents the largest part of the nervous system, and includes the brain and the spinal cord. The brain is the central control of the nervous system, and the spinal cord carries nerve impulses between the brain and the body, and from the body to the brain.
- The sense organs include the eyes, ears, nose, mouth, and skin. They all have sensory receptors that are specific for certain stimuli. The eyes have photoreceptors for sight. The ears have mechanoreceptors that interpret stimuli as sound and also endolymph that aids in body balance. The nose has chemoreceptors for odors. The mouth has chemoreceptors for taste. The skin has a variety of mechanoreceptors and baroreceptors for touch.
- Psychoactive drugs affect how neurons in the CNS communicate with each other. In this way a psychoactive drug changes how we feel, think, and interact with the world. Medicinal uses of psychoactive drugs include their use as anesthetics, painkillers, and antidepressants.
- For an animation of the neuromuscular junction see http://www.youtube.com/watch?v=ZscXOvDgCmQ.

Review Questions

1. How does the body transmit electrical signals?
2. Describe the structure of a neuron.
3. Distinguish between a neuron and a glial cell.
4. Use 20.35 of an action potential to answer the following questions.
   What is the membrane potential at the peak (after 2 milliseconds)? Is it positive or negative?
5. What happens to the membrane potential after 5 ms?
6. At the peak point when the membrane potential is 40mV, does the cell have an overall negative charge or positive charge?
7. Hyperpolarization, which means the cell becomes more negatively charged than it is at resting potential (more negative than -70 mV),can happen as a result of the binding of

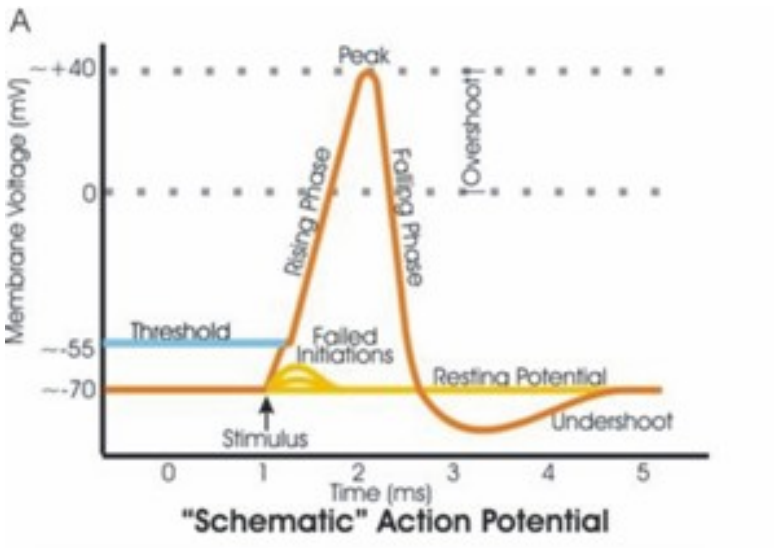

Figure 20.35

an inhibitory neurotransmitter to its receptor. Propose what happens to sodium and potassium ions during hyperpolarization.

8. How does voltage relate to the membrane potential?
9. What would happen to a cell if its sodium and potassium pumps failed to work at the end of an action potential?
10. The backflow of a nerve impulse is prevented by the fact that at a chemical synapse, the axon terminal does not have neurotransmitter receptors and dendrites cannot secrete neurotransmitter chemicals. What does this statement tell you about the direction of nerve impulses in neurons?
11. Identify two types of synapses in the nervous system.
12. What is the purpose of the digestive enzymes found in the synaptic cleft?
13. Distinguish a neurotransmitter from a hormone.
14. What is the major function of the central nervous system?
15. Outline the major functions of the cerebral cortex.
16. Use 20.36 of the lobes of the brain to answer the following questions.
    What is the name of the blue structure?
17. Identify a sense that is interpreted in the yellow-colored lobe (center left), and name that lobe.
18. Identify the two main divisions of the peripheral nervous system, and describe their roles in the body.
19. What are the two divisions of the autonomic nervous system?
20. Distinguish between the sympathetic and parasympathetic nervous systems.
21. What type of sensory receptors are found in the eyes?
22. Distinguish between rods and cones.
23. Why are taste and smell called the “two chemical senses”?

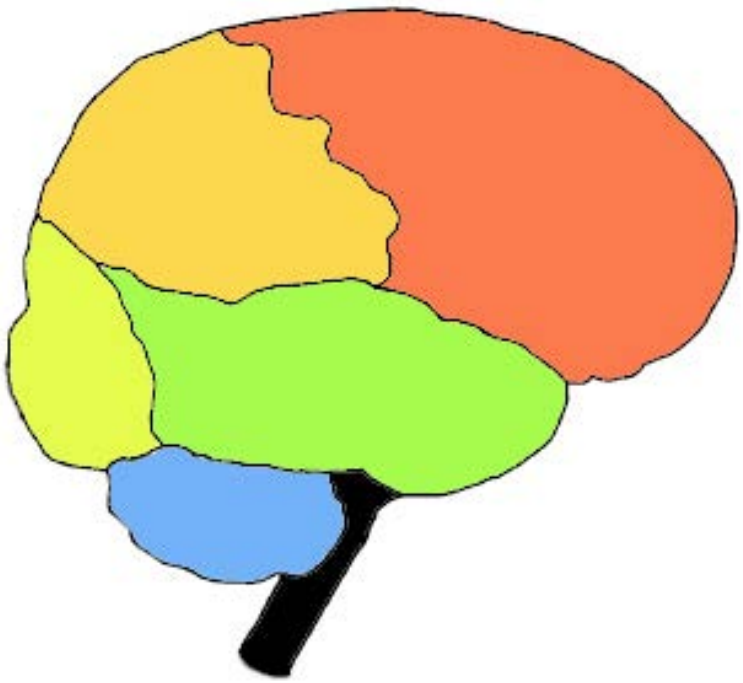

Figure 20.36

24. Outline how the ear is important to the sense of body balance.
25. What role does skin have in detecting external stimuli?
26. What kind of effects should a drug have for it to be called *psychoactive*?
27. Identify the main effect of psychoactive drugs on the CNS.
28. How do the effects of a stimulant differ from the effects of a depressant?
29. What is the brain reward system and how is it affected by an addictive drug?
30. How does cocaine affect the brain reward system?
31. Use 20.37 that shows the differences in blood concentration of nicotine over time to answer the following questions.
32. Review the graph that illustrates the increases in blood-nicotine concentrations from four different forms of tobacco; Cigarettes, oral snuff, chewing tobacco, and nicotine gum. Which of the four forms of nicotine increases blood-nicotine concentration the fastest?
33. Which of the four forms of nicotine increases blood-nicotine concentration the least?
34. Can you tell from this graph whether one form of tobacco is safer than another?

Further Reading / Supplemental Links

- http://training.seer.cancer.gov/module_anatomy/unit5_2_nerve_tissue.html
- http://brainmaps.org/

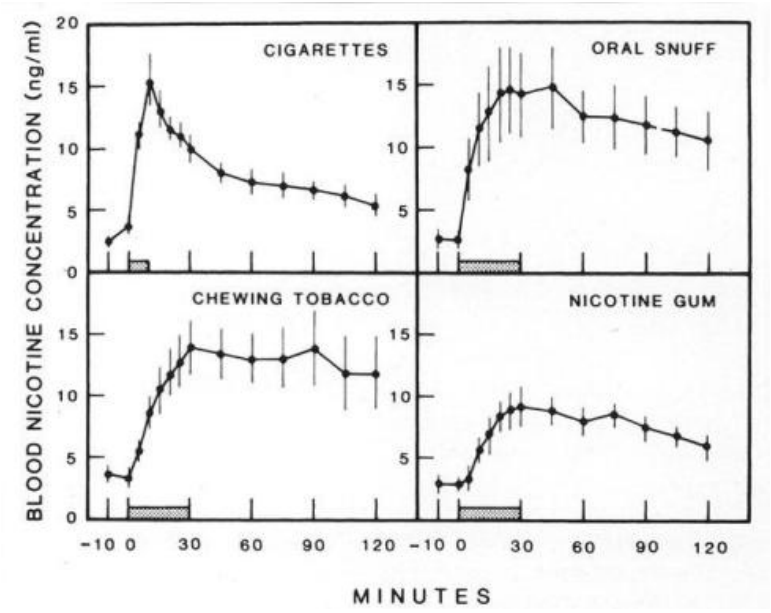

Figure 20.37

- http://teens.drugabuse.gov/index.asp
- http://www.nida.nih.gov/scienceofaddiction

Vocabulary

action potential An electrical charge that travels along the membrane of a neuron.

agonists Drugs that increase activity in particular neurotransmitter systems; act by increasing the synthesis of one or more neurotransmitters or reducing its reuptake from the synapses.

antagonists Drugs that reduce neurotransmitter activity; work by interfering with synthesis or blocking postsynaptic receptors so that neurotransmitters cannot bind to them.

astrocytes A type of glial cell in the brain; important for the maturation of neurons and may be involved in repairing damaged nervous tissue.

autonomic nervous system (ANS) The part of the peripheral nervous system that maintains homeostasis in the body; controls such actions as heart rate, digestion, respiration rate, salivation, and perspiration; also called the involuntary nervous system.

axon A long, membrane-bound extension of the cell body that passes the nerve impulse onto the next cell.

axon terminal The end of the axon; the point at which the neuron communicates with the next cell.

brain stem Part of the brain involved with unconscious (autonomic) functions such as breathing, heartbeat, and temperature regulation; contains the midbrain, the pons, and the medulla oblongata.

cerebellum The part of the brain that is involved in coordination and control of body movement.

cerebral cortex The highly-folded outer layer of the cerebrum; controls higher functions, such as consciousness, reasoning, emotions, and language; also controls sensory functions such as touch, taste, smell, and responses to external stimuli.

cerebrum The part of the brain that generally controls conscious functions such as problem-solving and speech.

central nervous system (CNS) Made up of the brain and spinal cord; the brain is the central control of the CNS; the spinal cord carries nerve impulses from the brain to the body and from the body to the brain.

chemical synapse A synapse that uses chemical signaling molecules as messengers.

cochlea A coiled tube within the ear; filled with a watery liquid which moves in response to the vibrations coming from the middle ear through the oval window; as the fluid moves, thousands of mechanoreceptors called hair cells bend, releasing a neurotransmitter.

cone cells Photosensitive cells important to vision; located in the retina; respond to different wavelengths of bright light to initiate a nerve impulse; also responsible for the sharpness of images.

dendrites Extend from the cell body and receive a nerve impulse from another cell.

diencephalons The region of the brain that includes structures such as the thalamus, the hypothalamus, and a portion of the pituitary gland.

dorsal root The "nerve highway;" carries sensory information from sensory receptors in the body to the CNS.

drug Any chemical or biological substance that affects the body's structure or functions.

drug abuse The repeated use of a drug without advice or guidance of a medical professional, and use for reasons other than for what the drug was originally intended.

electrical synapse Synapse that uses ions as messengers.

endocrine system A system of glands around the body that release chemical signal molecules into the bloodstream.

glial cell Cell that provides a support system for the neurons; also involved in synapse formation.

hallucinogens Psychedelic drugs, such as lysergic acid diethylamide (LSD), phencyclidine (PCP), and ketamine; psychoactive drugs that do not increase or decrease a certain feeling or emotion, but rather they induce experiences, such as sensory distortions and "out-of-body experiences," that are very different from those of ordinary consciousness.

hearing The sense of sound perception that results from the movement of tiny hair fibers in the inner ear.

hypnotics (depressants) Drug that decreases the activity of the central nervous system; slows down brain function and give a drowsy or calm feeling; includes alcohol, codeine, barbiturates, and benzodiazepines.

interneurons Neurons that connect sensory and motor neurons in neural pathways that go through the CNS; also called association or relay neurons.

medicine (or medication) A drug that is taken to cure or reduce the symptoms of an illness.

membrane potential The voltage across a membrane; the basis for the conduction of nerve impulses along the cell membrane of neurons.

midbrain Part of the brain involved with unconscious (autonomic) functions such as breathing, heartbeat, and temperature regulation.

motor division Subdivision of the PNS; carries nerve impulses from the CNS to the muscles, glands and organs of the body; also called the efferent division.

motor neurons Neurons that carry signals from the central nervous system to muscles and glands; sometimes called efferent neurons.

myelin sheath An electrically insulating phospholipid layer; covers the axon; speeds up the transmission of a nerve impulse along the axon.

nerve An enclosed, cable-like bundle of axons.

nervous system A complex network of nervous tissue that sends electrical and chemical signals; includes the central nervous system (CNS) and the peripheral nervous system (PNS) together.

neuromuscular junction A synapse between a neuron and a muscle cell.

neuron The "conducting" cell that transmits electrical signals; the structural unit of the nervous system.

neurotransmitter Chemical messages which are released at the synapse and pass the "message" onto the next neuron or other type of cell.

nociceptor A type of pain receptor which responds to potentially damaging stimuli.

Nodes of Ranvier Regularly spaced gaps between the myelin; the only points at which ions can move across the axon membrane, through ion channels.

olfactory receptors The chemoreceptors of smell.

oligodendrocytes Glial cells that supply myelin to neurons of the brain and spinal cord.

parasympathetic division Subdivision of the ANS; controls non-emergency functions such as digestion.

peripheral nervous system (PNS) Made up of the nervous tissue that lies outside the CNS, such as the nerves in the legs, arms, hands, feet and organs of the body.

pinna The folds of cartilage surrounding the outer ear canal; gathers sound waves which are channeled down the auditory canal, a tube-shaped opening of the ear which ends at the tympanic membrane, or eardrum.

psychoactive drug A substance that affects the central nervous system by altering cognitive function.

reflex An automatic (involuntary) action caused by a defined stimulus and carried out through a reflex arc.

resting potential The resting state of the neuron, during which the neuron has an overall negative charge.

reuptake The removal of a neurotransmitter from the synapse by the pre-synaptic neuron; a way of controlling the effect the neurotransmitter has on the post-synaptic cell.

rod cells Photosensitive cells important to vision; located in the retina; highly sensitive to light which allows them to respond in dim light and dark conditions, but, they cannot detect color.

Schwann cells Cells that supply the myelin for neurons that are not part of the brain or spinal cord.

sensory division Subdivision of the PNS; carries sensory information from sensory receptors in the body to the CNS; also known as the afferent division.

sensory neurons Neurons that carry signals from tissues and organs to the central nervous system; sometimes called afferent neurons.

sight (vision) Describes the ability of the brain and eye to detect certain wavelengths of electromagnetic radiation (light), and interpret the image.

sodium-potassium pump Transport protein that removes Na^+ ions from the cell by active transport; also brings K^+ ions into the cell.

somatic nervous system The part of the PNS that is associated with the conscious (voluntary) control of the body through the movement of skeletal muscles and the perception of external stimuli through senses such as touch, hearing, and sight.

spinal cord A thin, tubular bundle of nervous tissue that extends from the medulla oblongata and continues to the lower back; functions as an information superhighway that links the sensory messages from the body to the brain.

stimulant Psychoactive drug, such as cocaine, nicotine, and amphetamine, that increases the activity of the sympathetic nervous system, the central nervous system, or both; generally increase heart rate, blood pressure, and increase the sense of alertness.

sympathetic division Subdivision of the ANS; generally stimulates body systems during emergency situations.

synapse A specialized junction at which neurons communicate with each other.

synaptic cleft Gap between the axon terminal of the presynaptic neuron and the receiving cell.

threshold Level of depolarization the membrane potential has to surpass for the action potential to start.

touch The sense of pressure perception, which is generally felt in the skin.

ventral root Contains axons of motor neurons which carry information away from the CNS to the muscles and glands of the body.

voltage Electrical potential energy that is caused by a separation of opposite charges.

Points to Consider

- The electrical signals of the nervous system move very rapidly along nervous tissue, while the chemical signals of the endocrine system act much more slowly and over a longer period of time. Identify some of advantages to having two different speeds for communications in the body.
- Identify ways that psychoactive drug abuse may negatively affect organ systems other than the nervous system.
- The cerebral cortex controls functions such as consciousness, reasoning, emotions, and language. The brain stem is the lower part of the brain that is involved with unconscious, autonomic functions. Consider why consciousness and reasoning are called "higher functions" in relation to the "lower functions" of breathing and heartbeat.

20.2 Lesson 20.2: The Endocrine System

Lesson Objectives

- Identify the main functions of the endocrine system.
- Identify the structures that produce hormones.
- Outline how hormones affect certain cells and not others.
- Describe two ways that hormones influence the function of cells.
- Identify the two glands that serve as the major control centers of the endocrine system.
- Identify the effects of adrenal hormones on the body.
- Examine the importance of the islets of Langerhans.
- Outline the role of the sex hormones in reproduction.
- Identify non-endocrine organs that secrete hormones.
- Examine how feedback mechanisms control hormone levels and body functions.
- Identify the role of hormone antagonists in the control of substances in the body.
- Identify two medical uses of hormones.

Introduction

The **endocrine system** is a system of organs that releases chemical message molecules, called hormones, into the blood. Unlike the nervous system whose action helps the body react immediately to change, such as quickly jumping out of the way of an oncoming cyclist, the endocrine system controls changes that happen to the body over a long period of time; from minutes, hours, to years of change. The two systems work closely together to help us respond to our environment, such as the rollercoaster ride shown in **Figure** 20.38. The endocrine system is important in controlling metabolism, growth and development, reproduction, and salt, water and nutrient balance of blood and other tissues (osmoregulation).

Function of the Endocrine System

The nervous system uses nerves to conduct electrical and chemical information around the body, while the endocrine system uses blood vessels to carry chemical information. You can think of the nervous system as being similar to the electrical system in a house. Flicking on a light switch is similar to initiating an action potential in a nerve, and it has an almost immediate result: the light bulb illuminates. The endocrine system on the other hand is more like starting up an oil or gas powered water-heating system. You flick on the switch to heat water up for a bath, but it takes a certain length of time for the result to occur: hot water.

Figure 20.38: What an adrenaline rush! The excitement that the people on this rollercoaster are feeling is a good example of how the nervous and endocrine systems work together. Nerve impulses from the sympathetic nervous system cause the adrenal medulla to release the hormone adrenaline into the bloodstream. Adrenaline causes the racing heart, sweaty palms, and feeling of alertness that together are called the "fight or flight" response.

Organs of the Endocrine System

The endocrine system is made up of many glands that are located in different areas of the body. **Hormones** are chemical messenger molecules that are made by cells in one part of the body and cause changes in cells in another part of the body. Hormones regulate the many and varied functions that keep you alive.

Hormones are made and secreted by cells in endocrine glands. **Endocrine glands** are ductless organs that secrete hormones directly into the blood or the fluid surrounding a cell rather than through a duct. The primary function of an endocrine gland is to make and secrete hormones. The endocrine glands collectively make up the **endocrine system**. The major glands of the endocrine system and their functions are shown in **Figure** 20.39. Many other organs, such as the stomach, heart, and kidneys secrete hormones and are considered to be part of the endocrine system.

Exocrine glands are organs that secrete their products into ducts (they are duct glands). They are similar to endocrine glands in that they secrete substances, but they do not secrete hormones. Instead they secrete products such as water, mucus, enzymes, and other proteins through ducts to specific locations inside and outside the body. For example, sweat glands secrete sweat onto the skin and salivary glands secrete saliva into the mouth. The reason we are discussing exocrine glands in a chapter about hormones is because some endocrine glands, such as the pancreas, are also exocrine glands. Ducts in the pancreas secrete fat-digesting enzymes into the intestines. The secretion of the enzymes from the pancreas is

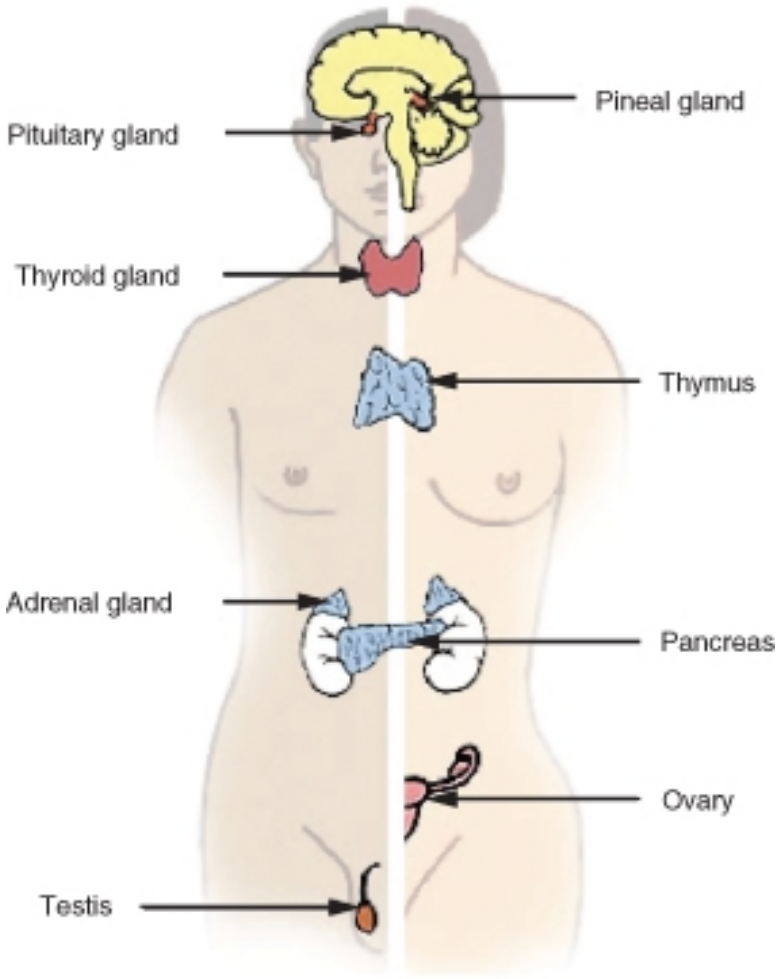

Figure 20.39: The major organs of the endocrine system.

controlled by hormones that are made by certain stomach cells.

Hormones

The body produces many different hormones, but each hormone is very specific for its target cells. A **target cell** is the cell on which a hormone has an effect. Target cells are affected by hormones because they have receptor proteins that are specific to the hormone. Hormones will travel through the bloodstream until they find a target cell with the specific receptors to which they can bind. When a hormone binds to a receptor, it causes a change within the cell.

There are two main types of hormones, and a group of hormone-like substances:

- **Amino Acid-Based Hormones**

Amino acid-based hormones are made of amino acids. Some amino acid-based hormones are made of a few amino acids and are simple in structure while others are made of hundreds of amino acids and are very large. These hormones are not fat-soluble and therefore cannot diffuse through the plasma membrane of their target cell. They usually bind to receptors that are found on the cell membrane.

- **Cholesterol-Based Hormones**

Cholesterol-based hormones are made of lipids such as phospholipids and cholesterol. Hormones from this group are also called steroid hormones. Steroid hormones are fat soluble and are able to diffuse through the plasma membrane. Steroid hormone receptors are found within the cell cytosol and nucleus.

- **Hormone-like Substances**

The term hormone-like substances refers to a group of signaling molecules that are derived from certain types of fatty acids and proteins. Two examples of these substances are prostaglandins and neuropeptides. These substances do not travel around the body in blood as hormones do and tend to be broken down quickly. As a result, the effects of hormone-like substances are localized in the tissue in which it they are produced. For example, **prostaglandins**, which are made from essential fatty acids, are produced by most cells in the body. Prostaglandins have many different effects such as causing constriction or dilation of blood vessels but they are all are localized within the target cells and tissues. **Neuropeptides** are signaling peptides found in nervous tissue. Neuropeptides have many effects on nerve cells. For example, they can affect gene expression, local blood flow, and the shape of glial cells. Some neuropeptides such as endorphins and oxytocin have effects on non-nerve cells and are called hormones. Both signaling molecules have an effect on behavior. Among

other things, endorphins are involved in pain perception and oxytocin is involved in social bonding and maternal behavior.

The cells that make hormones are usually specialized for the job, and are found within a particular endocrine gland, for example the thyroid gland, the ovaries, or the testes. Hormones may exit their cell of origin by exocytosis or another type of membrane transport. Typically cells that respond to a particular hormone may be one of several cell types that are found in different tissues throughout the body. Such is the case for insulin, which triggers a great number of physical effects. Different tissue types may also respond differently to the same hormonal signal. Because of this, hormonal signaling is a very complex process.

Hormone Receptors

Cells that respond to hormones have two properties in common: they have receptors that are very specific for certain hormones, and those receptors are joined with processes that control the metabolism of the target cells. There are two main ways that receptor-bound hormones activate processes within cells, depending on whether the hormone can pass across the membrane (steroid hormones are fat-soluble), or cannot pass through the membrane (most amino acid based hormones are water soluble).

- **Second Messenger System**

A water-soluble hormone molecule does not enter the cell, instead it binds to the membrane-bound receptor molecule, which triggers changes within the cell. These changes are activated by second messenger molecules.

- **Direct Gene Activation**

A fat-soluble hormone diffuses across the membrane and binds to the receptor within the cytosol or nucleus. The hormone-receptor complex then acts as a transcription factor that affects gene expression.

The two different ways that hormones can activate cells are discussed here, using the amino-acid based hormone glucagon and the steroid hormone cortisol as examples.

Action of Glucagon: A Second Messenger System

The majority of amino-acid based hormones, such as glucagon, bind to membrane-bound receptors. The binding of the hormone triggers a **signal transduction pathway**, a process of molecular changes that turns the hormone's extracellular signal into an intracellular response. Activation of these receptors by hormones (the first messengers) leads to the intracellular production of second messengers as part of the signal transduction pathway. A

second messenger is a small molecule that starts a change inside a cell in response to the binding of a specific signal to a receptor protein. Some second messenger molecules include small molecules such as cyclic AMP (cAMP), cyclic GMP (cGMP), and calcium ions (Ca^{2+}).

Glucagon is an important hormone involved in carbohydrate metabolism. It is released when the glucose level in the blood is low which causes the liver to change stored glycogen into glucose and release it into the bloodstream. Glucagon is released by the pancreas and circulates in the blood until it binds to a glucagon receptor, a G protein-linked receptor, found in the plasma membrane of liver cells. The binding of glucagon (first messenger) changes the shape of the receptor, which then activates a G protein. The G-protein is an enzyme that in turn activates the next enzyme in the cascade, the second messenger; adenylate cyclase. Adenylate cyclase produces cAMP which activates another enzyme, which in turn activates another enzyme, and so on. The end result is an enzyme that breaks apart the glycogen molecule in the liver cell to release glucose molecules into the blood. The signal transduction pathway, a type of enzyme "domino-effect" inside the cell, allows a small amount of hormone to have a large effect on the cell or tissue. To learn more about second messenger systems, refer to the *Cell Structure and Function* chapter.

Action of Cortisol: A Direct Gene Activation

Steroid hormones diffuse through cell membrane and bind to receptors in the cytosol or the nucleus of the cell. The receptor-hormone complex acts as a transcription factor that affects gene expression.

Cortisol is a steroid hormone produced by the adrenal glands. It is often called the "stress hormone" as it is involved in the body's response to stress. It increases blood pressure, blood sugar levels and has an immunosuppressive action. Cortisol crosses the cell membrane and binds to a steroid receptor in the cytoplasm. The cortisol-receptor complex then enters the nucleus of the cell and binds to DNA, where it activates or deactivates gene transcription. The gene that is activated or deactivated depends on the cell type.

Effects of Hormones

The effects of hormones vary widely, and certain hormones, called tropic hormones (or tropins), regulate the production and release of other hormones. Many of the responses to hormones regulate the metabolic activity of an organ or tissue.

Other effects of hormones can include:

- Stimulation or inhibition of growth
- Induction or suppression of programmed cell death (apoptosis)
- Activation or inhibition of the immune system
- Regulation of metabolism

- Preparation for a new activity (e.g., fighting, fleeing, mating)
- Preparation for a new phase of life, for example puberty, caring for offspring, or menopause
- Control of the reproductive cycle

You will learn more about the effects of certain hormones as we examine some of the endocrine glands individually.

Hypothalamus and Pituitary Gland

The **hypothalamus** links the nervous system to the endocrine system by the pituitary gland. The hypothalamus is located below the thalamus, just above the brain stem. It is found in all mammalian brains, including humans. The human hypothalamus is about the size of an almond; its position in the brain is shown in **Figure** 20.40.

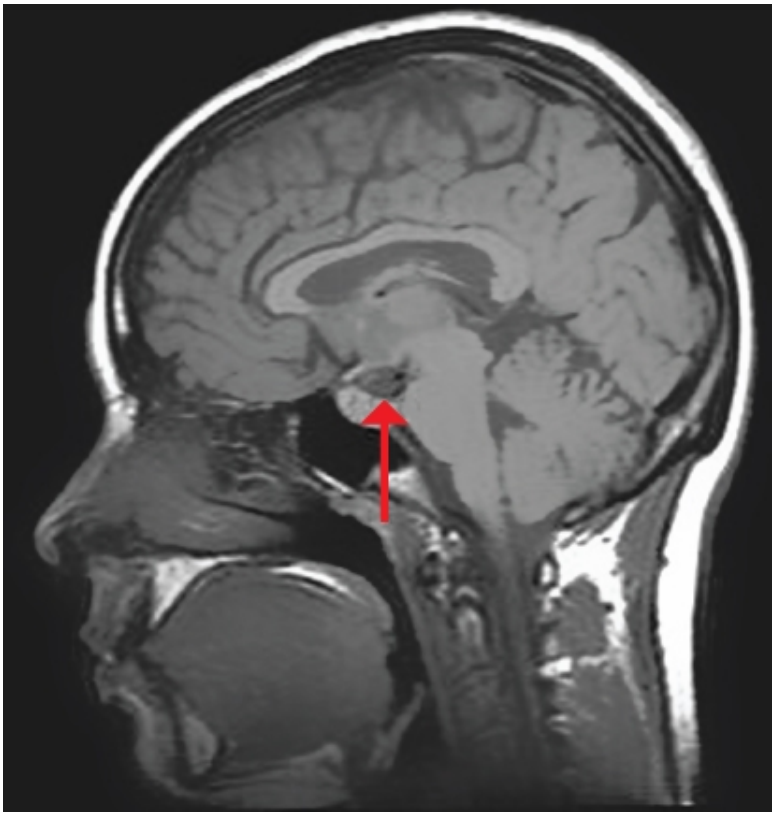

Figure 20.40: The hypothalamus is here. The red arrow shows the position of the hypothalamus in the brain.

The hypothalamus is a very complex area of the brain, and even small numbers of nerve cells within it are involved in many different functions. The hypothalamus coordinates many sea-

sonal and circadian rhythms, complex homeostatic mechanisms, and the autonomic nervous system (ANS). A **circadian rhythm** is a roughly-24-hour cycle in the biological processes carried out within organisms, including plants, animals, fungi and certain bacteria. The ANS controls activities such as body temperature, hunger, and thirst. The hypothalamus must therefore respond to many different signals, some of which are from outside and some from inside the body. Thus, the hypothalamus is connected with many parts of the CNS, including the brainstem, the olfactory bulbs, and the cerebral cortex.

The hypothalamus produces hormones that are stored in the pituitary gland. For example, oxytocin and antidiuretic hormone (ADH) are made by nerve cells in the hypothalamus, and are stored in the pituitary prior to their release into the blood. In addition to influencing maternal behavior, oxytocin is involved in controlling circadian homeostasis, such as a person's body temperature, activity level, and wakefulness at different times of the day. Antidiuretic hormone (ADH) is released when the body is low on water; it causes the kidneys to conserve water by concentrating the urine and reducing urine volume. It also raises blood pressure by causing blood vessels to constrict.

Pituitary Gland

The **pituitary gland** is about the size of a pea and is attached the hypothalamus by a thin stalk at the base of the brain, shown in **Figure** 20.41. The pituitary gland secretes hormones that regulate homeostasis. It also secretes hormones that stimulate other endocrine glands, called tropic hormones.

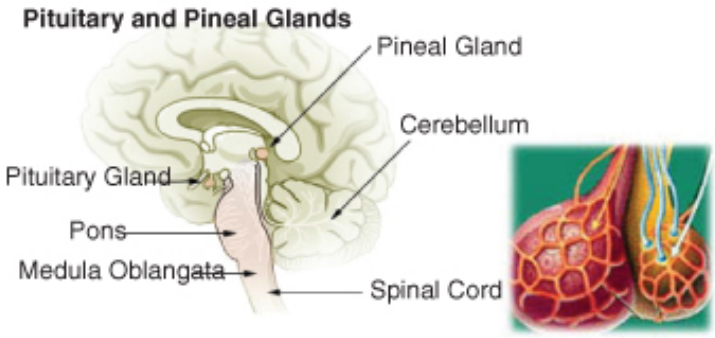

Figure 20.41: The position of the pituitary in the brain. A close-up of the anterior and posterior pituitary gland can be seen at right. The orange vessels are the capillary system that comes from the hypothalamus and carries hormones to the anterior pituitary (red) for storage. The blue vessels on the posterior pituitary come from the neurosecretory cells in the hypothalamus.

The **anterior pituitary**, or front lobe, makes many important hormones, which are listed

in **Table** 20.5. The **posterior pituitary**, or rear lobe, releases two hormones, oxytocin and antidiuretic hormone (ADH) that are made by nerve cells in the hypothalamus. These hormones are transported down the nerve cell's axons to the posterior pituitary where they are stored until needed.

Table 20.5: **Pituitary Hormones**

Location	Hormone	Target	Function
Anterior Pituitary	Adrenocorticotropic hormone (ACTH) Thyroid-stimulating hormone (TSH) Growth hormone (GH) Follicle stimulating hormone (FSH) Leutinizing hormone (LH) Prolactin (PRL)	Adrenal Gland Thyroid Gland Body cells Ovaries, Testes (Gonads) Ovaries, Testes Ovaries, mammary glands	Stimulates adrenal cortex Stimulates thyroid Growth hormone Stimulates production of ovarian follicles in females, sperm production in males Causes ovulation in females Causes milk secretion
Posterior Pituitary	Anti diuretic hormone (vasopressin) Oxytocin	Kidneys or Arterioles uterus, mammary glands	Promotes water reabsorption in kidneys, raises blood pressure Causes uterus to contract in childbirth, stimulates milk flow

Most of these hormones are released from the anterior pituitary under the influence of hormones from the hypothalamus. The hypothalamus hormones travel to the anterior lobe down a special capillary system that surrounds the pituitary.

Oxytocin is the only pituitary hormone to create a positive feedback loop. For example, during the labor and delivery process, when the cervix dilates the uterus contracts. Uterine contractions stimulate the release of oxytocin from the posterior pituitary, which in turn increases uterine contractions. This positive feedback loop continues until the baby is born.

Other Endocrine Glands

Thyroid and Parathyroid Glands

The **thyroid** is one of the largest endocrine glands in the body. This butterfly-shaped gland is found in the neck, wrapped around the trachea, as shown in **Figure** 20.42. The hormones released by the thyroid control how quickly the body uses energy, makes proteins, and how sensitive the body should be to other hormones. The thyroid is controlled by the hypothalamus and pituitary. Thyroid hormone generally controls the pace of all of the processes in the body. This pace is related to your metabolism. If there is too much thyroid hormone, every function of the body tends to speed up. The thyroid gland regulates the body temperature by secreting two hormones that control how quickly the body burns calories. Hyperthyroidism (overactive thyroid) and hypothyroidism (under active thyroid) are the most common problems of the thyroid gland.

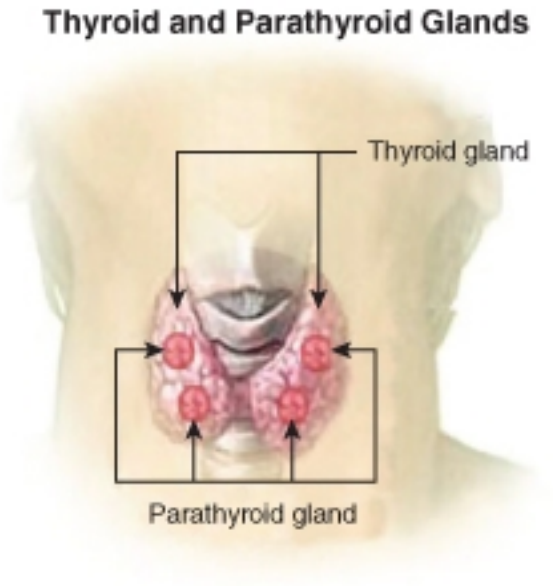

Figure 20.42: The position of the thyroid and parathyroid glands. A person can have more than four parathyroid glands.

The thyroid hormones thyroxine (T4) and triiodothyronine (T3) regulate the rate of metabolism and affect the growth and rate of function of many other systems in the body. As a result, problems with the under secretion or over secretion of thyroid hormones affect many body systems.

The element iodine is very important for making both T3 and T4. If a person's diet does not have enough iodine, their thyroid cannot work properly and the person develops an iodine

deficiency disease called **goiter**. Low amounts of T3 and T4 in the blood, due to lack of iodine to make them, causes the pituitary to secrete large amounts of thyroid stimulating hormone (TSH), which causes abnormal growth of the thyroid gland. The addition of small amounts of iodine to mass produced foods, such as table salt, has helped reduce the occurrence of iodine-deficiency in developed countries. The thyroid also produces the hormone calcitonin, which plays a role in calcium homeostasis. The hormones secreted by the thyroid are listed in **Table** 20.6.

Table 20.6: **Hormones Secreted by the Thyroid and Parathyroid Glands**

Location	Hormone	Target	Function
Thyroid	Triiodothyroine (T3) Thyroxine (T4) Calcitonin	Body Cells Bone cells	Increase metabolic rate, stimulates mental and physical growth Increases calcium absorption by bones, lowers blood calcium level
Parathyroid	Parathyroid hormone (PTH)	Cells of the bone, kidney, and intestines	Regulates blood calcium levels

Parathyroid Glands

The parathyroid glands are usually located behind the thyroid gland, but they are visible in **Figure** 20.42. Parathyroid hormone (PTH), maintains blood calcium levels within a narrow range, so that the nervous and muscular systems can work properly. When blood calcium levels drop below a certain point, calcium-sensing receptors in the parathyroid gland release the hormone parathyroid hormone (PTH) into the blood. PTH has effects that are opposite to the action of calcitonin. It increases blood calcium levels by stimulating certain bone cells to break down bone and release calcium. It also increases gastrointestinal calcium absorption by activating vitamin D, and promotes calcium uptake by the kidneys. The hormones secreted by the parathyroid glands are listed in **Table** 20.6.

Pineal Gland

The hormone melatonin is made in the pea-sized pineal gland, which is located at the base of the brain. Production of melatonin by the pineal gland is under the control of the hypothalamus which receives information from the retina about the daily pattern of light and darkness. Very little is currently known about the functions of melatonin, but scientists have

found that it is involved in sleep cycles (circadian cycles), the onset of puberty, and immune function. Melatonin secretion also responds to seasonal changes in light, which could be a reason why getting out of bed on a dull, rainy morning can be so difficult, as the boy in **Figure** 20.43 probably knows.

Figure 20.43: Very little is currently known about the role of melatonin, but scientists do know that it is involved in sleep cycles. It is produced by the pineal gland, the retina and the intestines. Production of melatonin by the pineal gland is influenced of by the hypothalamus which receives information from the retina about the daily pattern of light and darkness.

Pancreas

The **pancreas** is both an exocrine gland as it secretes pancreatic juice containing digestive enzymes, and an endocrine gland as it produces several important hormones. It is located just

below and behind the stomach, as shown in **Figure** 20.44. The endocrine cells of the pancreas are grouped together in areas called **islets of Langerhans**, shown in **Figure** 20.45. The islets produce the amino acid-based hormones insulin, glucagon, and somatostatin. Insulin and glucagon are both involved in controlling blood glucose levels. **Insulin** is produced by beta cells and causes excess blood glucose to be taken up by liver and muscle cells, where it is stored as glycogen, a polysaccharide. **Glucagon** is produced by alpha cells and stimulates liver cells to break down stores of glycogen into glucose which is then released into the blood. An alpha cell is another type of endocrine cell that is found within the islets of Langerhans. The hormones secreted by the pancreas are listed in **Table** 20.7.

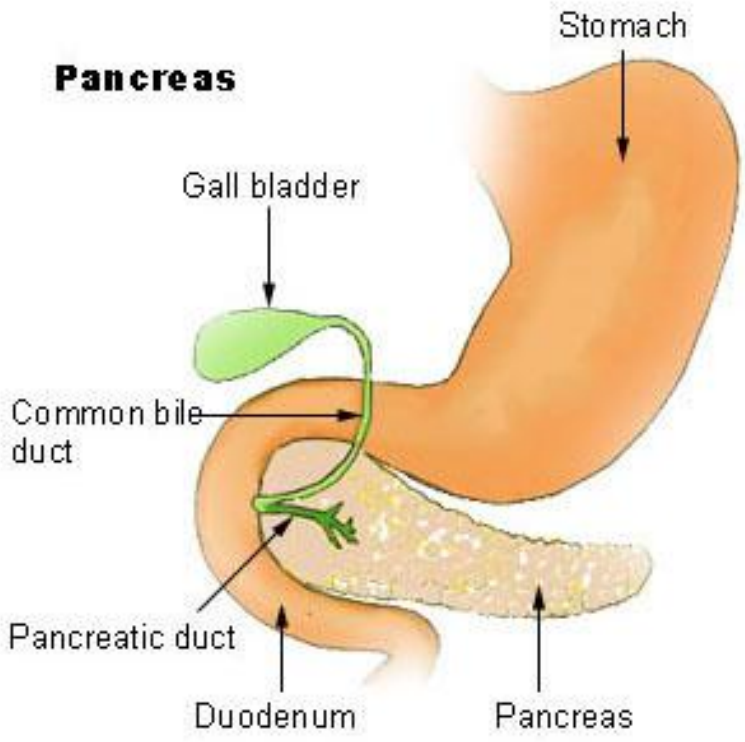

Figure 20.44: The location of the pancreas in relation to the stomach and gall bladder. The hormone-producing Islet cells a found in groups throughout the pancreas.

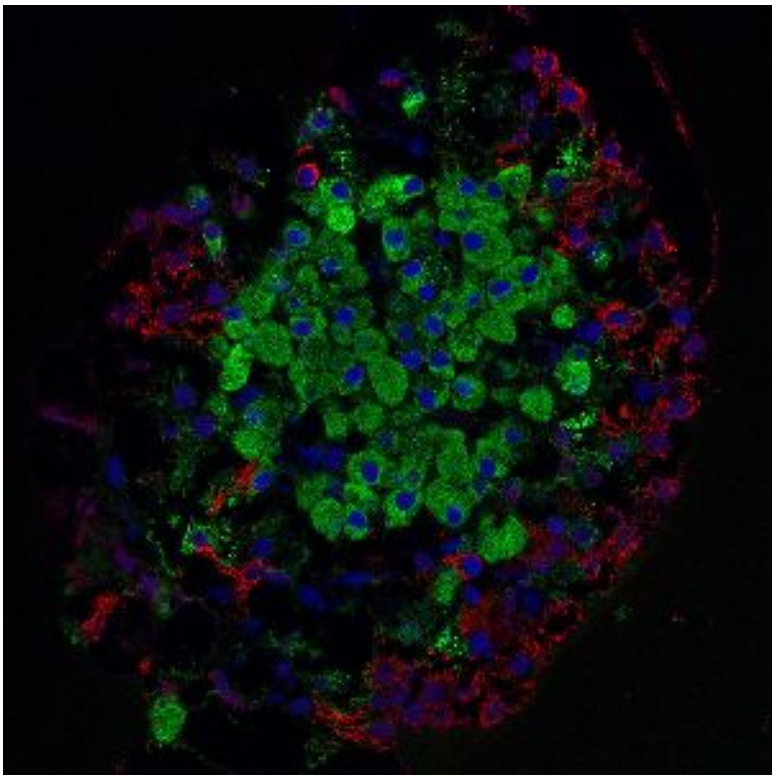

Figure 20.45: Micrograph of an islet of Langerhans isolated from a rat pancreas. Each islet in a human pancreas contains approximately 1000 cells and is 50 to 500 micrometers in diameter. Cell nuclei are stained blue, insulin-producing beta cells are green, and glucagon-producing alpha cells are red.

Table 20.7: **Hormones Secreted by the Pancreas**

	Hormone	Effects
	Insulin Glucagon Amylin Somatostatin (inhibitory hormone) Ghrelin	Reduces blood glucose concentration Raises blood glucose concentration Suppresses glucagons secretion Suppress the release of insulin, glucagon, and pancreatic enzymes Stimulates appetite

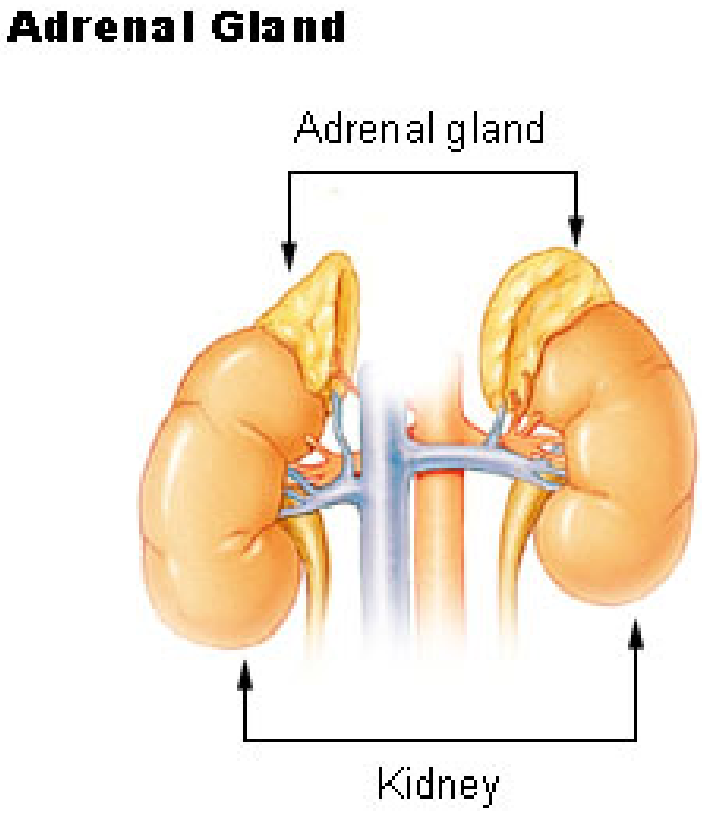

Figure 20.46: The location of the adrenal glands, above the kidneys.

Adrenal Glands

An adrenal gland is located above each of the kidneys, as shown in **Figure** 20.46. Each adrenal gland is separated into two structures, the adrenal medulla, which is the center of the gland, and the adrenal cortex, which is the outer layer. The medulla and the cortex work as two separate endocrine glands.

The **adrenal medulla** is the core of the adrenal gland, and is surrounded by the adrenal cortex. Secretion of hormones from the medulla is controlled by the sympathetic nervous system. The cells of the medulla are the body's main source of the hormones **adrenaline** (epinephrine) and **noradrenaline** (norepinephrine). These hormones are part of the fight-or-flight response initiated by the sympathetic nervous system. The hormone boosts the supply of oxygen and glucose to the brain and muscles, while suppressing other non-emergency bodily processes, such as digestion.

The **adrenal cortex** is the site of steroid hormone synthesis. Some cells make cortisol, while other cells make androgens such as testosterone. Other cells of the cortex regulate water and electrolyte concentrations by secreting aldosterone, which helps to regulate blood pressure. In contrast to the medulla that is controlled directly by the nervous system, the cortex is regulated by hormones secreted by the pituitary gland and hypothalamus.

Cortisol is an important steroid hormone that is often called the "stress hormone" as it is involved in the response to stress, and is involved in restoring homeostasis after a stressful event, such as the (good) stress caused by running around a soccer field [football pitch (for non-American-English speakers)], shown in **Figure** 20.47. Cortisol increases blood pressure, blood sugar levels and has an immunosuppressive action. Long-term stress causes prolonged cortisol secretion, hyperglycemia, and weakening of the immune system. Excess levels of cortisol in the blood result in Cushing's syndrome, symptoms of which include rapid weight gain, a round face, excess sweating, and thinning of the skin and mucous membranes.

Figure 20.47: Regular activity through sport is a good way of allowing your body to respond naturally to its stress hormones, which prepare the body for quick movements or prolonged activity.

Table 20.8: **Hormones of the Adrenal Glands**

Location	Hormone	Function
Adrenal cortex		
	Mineralcorticoids (such as aldosterone)	Regulate sodium reabsorption and potassium elimination in the kidneys
	Glucocortocoids (such as cortisol)	Depress immune response, provide stress resistance, helps in fat, protein and carbohydrate metabolism
	Gonadotropins	Stimulates releases of sex hormones that develop sexual characteristics of males and females

Table 20.8: (continued)

Location	Hormone	Function
Adrenal medulla		
	Epinephrine (adrenaline)	"Fight or flight" hormone, plays central role in short-term response to stress, increases heart rate and supply of blood and oxygen to the brain
	Norepinephrine (noradrenaline)	Increases alertness, physical effect similar to epinephrine

Epinephrine, also called **adrenaline**, is a "fight or flight" hormone which is released from the adrenal medulla when stimulated by the sympathetic nervous system. Epinephrine plays a central role in the short-term stress reaction—the body's response to threatening, exciting, or environmental stressors such as high noise levels or bright light. When secreted into the bloodstream, it binds to multiple receptors and has many effects throughout the body. Epinephrine increases heart rate, dilates the pupils, and constricts blood vessels in the skin and gut while dilating arterioles in leg muscles. It increases the blood sugar level, and at the same time begins the breakdown of lipids in fat cells. It also "turns down" non-emergency bodily processes such as digestion. Similar to other stress hormones, such as cortisol, epinephrine depresses the immune system.

Stress also releases norepinephrine in the brain. **Norepinephrine** has similar actions in the body as adrenaline, such as increasing blood pressure. Norepinephrine is also psychoactive because it affects alertness, which would be helpful for studying as shown in **Figure** 20.48. The hormones secreted by the adrenal cortex and medulla are listed in **Table** 20.8.

Gonads

The ovaries of females and the testes of males are the gamete producing organs, or **gonads**. Ovaries in females are homologous to testes in males. In addition to producing gametes, an exocrine action, the gonads are endocrine glands that produce steroid sex hormones. **Sex hormones** are responsible for the secondary sex characteristics that develop at puberty. **Puberty** is the process of physical changes during which the sex organs mature and a person become capable of reproducing. During puberty, among other changes, males begin producing sperm and females begin menstrual cycles.

Figure 20.48: Thinking about an upcoming exam can cause your adrenal glands to produce adrenaline (epinephrine). Your body's stress response can cause you to feel "stressed out," but can also motivate you to study.

Luteinizing hormone (LH) and *follicle stimulating hormone* (FSH), which are both secreted by the pituitary gland, are called gonadotropes because they are tropic hormones of the gonads. Recall that tropic hormones trigger the production of hormones in other endocrine glands. The secretion of LH and FSH are, in turn, controlled by gonadotropin-releasing hormone for the hypothalamus. Those pulses, in turn, are subject to the estrogen feedback from the gonads.

In males LH triggers the production of sex hormones called **androgens** in the testes. The main androgen produced by the testes is **testosterone**. Testosterone causes an increase in skeletal muscle mass and bone density and is also responsible for the secondary sex characteristics of males such as facial hair, shown in **Figure** 20.49. The testes also produce small amounts of estrogen in the form of estradiol, which is believed to be important for sperm formation. On average, the human adult male body produces about eight to ten times more testosterone than an adult female body.

Table 20.9: **Hormones Produced by Gonads**

Organ	Hormone	Target	Function
Ovaries	Estrogen	Bone cells, cells of sex organs	Promotes growth and development of female sex organs Maintains Uterine lining

Table 20.9: (continued)

Organ	Hormone	Target	Function
Testes	Progesterone Testosterone	Bone cells, muscle cells, cells of sex organ	Stimulates growth and development of male sex organs and sex drive

Figure 20.49: The male hormone testosterone stimulates the growth of facial hair. Many men develop facial hair in the later years of puberty, usually between the ages of 15 to 18 years. The amount of facial hair on a man's face varies between individuals, and also between ethnic groups. For example, men from many East Asian or West African backgrounds typically have much less facial hair than those of Western European, Middle Eastern, or South Asian descent.

In females a rise in LH concentration triggers the production of estrogen and progesterone by the ovaries. Estrogen causes the release of an egg from the ovaries and progesterone prepares the uterus for a possible implantation by a fertilized egg. The placenta is an endocrine gland of pregnancy because it secretes the hormones estrogen, human chorionic gonadatropin, and progesterone which are important for maintaining a pregnancy, shown in **Figure** 20.50. The hormones secreted by the male and female gonads are listed in **Table** 20.9.

Figure 20.50: Maintaining correct hormone levels (especially progesterone), throughout pregnancy is important for carrying a pregnancy to full term.

Other Hormone-Producing Tissues and Organs

Several organs that are generally nonendocrine in function, such as the stomach, the small intestine, the kidneys, and the heart have cells that secrete hormones. For example, the kidneys secrete erythropoietin (EPO), a hormone that regulates red blood cell production, and the heart secretes atriopeptin, a hormone that reduces water and sodium levels in the blood, which decreases blood pressure. Ghrelin is a hormone that stimulates appetite and is produced by certain cells that line the stomach. Certain cancer cells secrete hormones that can interfere with homeostasis.

Regulation: Feedback Mechanisms

Hormones regulate many cell activities and so are important to homeostatic regulation. The rate of hormone production and secretion is often controlled by homeostatic feedback control

mechanisms, and the effect of hormones is also controlled by hormone antagonists. In these ways, the concentration of hormones and their products is kept within a narrow range so as to maintain homeostasis.

A **feedback control mechanism**, or a **feedback loop**, is a signaling system in which a product or effect of the system controls an earlier part of the system, either by shutting the process down or speeding it up. Most feedback mechanisms of the body are negative, only a few are positive. **Hormone antagonists** and **hormone receptor antagonists** are hormones or other molecules that block the action of hormones, and are also used by the body to control the action of hormones.

Negative Feedback

Negative feedback is a reaction in which the system responds in such a way as to reverse the direction of change. Since this tends to keep things constant, it allows for a process to return from a state of imbalance back to a homeostatic equilibrium.

A common, non-biological example of negative feedback happens in a home heating system. When you are home, you set your thermostat to 21 ˚ C (about 70 ˚ F), which is the **set point**. The thermometer in the thermostat monitors the room temperature and will sense when the temperature drops below the 21 ˚ C set point (the stimulus). The thermometer will then send a message to the thermostat (control center), which in turn sends a message to the furnace to switch on and heat up the room. When the room temperature returns to the set temperature, the thermostat shuts the furnace off. In this home-heating example, the increase in air temperature is the negative feedback that results in the furnace being shut off. In this way a set room temperature of 21 ˚ C (within a degree or two) is maintained.

An example of negative feedback in the body is the control of blood-glucose concentrations by insulin. A higher amount of glucose in the blood (the stimulus), signals the beta cells of the pancreas to release insulin into the blood. Hormone concentration alone cannot trigger a negative feedback mechanism, negative feedback is instead triggered by an overproduction of the effect of the hormone, such as the lowering of blood glucose concentration (the effect), which causes a decrease in the secretion of insulin by the pancreas.

Negative Feedback: Regulation of Thyroid Hormones

The thyroid hormones thyroxine (T4) and triiodothyronine (T3) regulate the rate of metabolism. The production of T4 and T3 is regulated by a thyroid-stimulating hormone (TSH), which is released by the anterior pituitary. The thyroid and the TSH-producing cells of the anterior pituitary form a negative feedback loop, as shown in **Figure** 20.51.

Thyroid-stimulating hormone production is decreased when the T4 levels are high, and when TSH levels are high, T4 production is decreased. The production and secretion of

TSH is in turn controlled by thyrotropin-releasing hormone (TRH), which is produced by the hypothalamus. The rate of TRH secretion is increased in situations such as cold temperature because increasing the metabolic rate would generate more heat. Increased levels of T4 and T3 in the blood cause a reduction in TRH secretion. Among other things, TSH secretion is reduced by high levels of thyroid hormones, as well as the antagonistic hormone somatostatin. These feedback loops keep the concentration of thyroid hormones within a narrow range of concentrations.

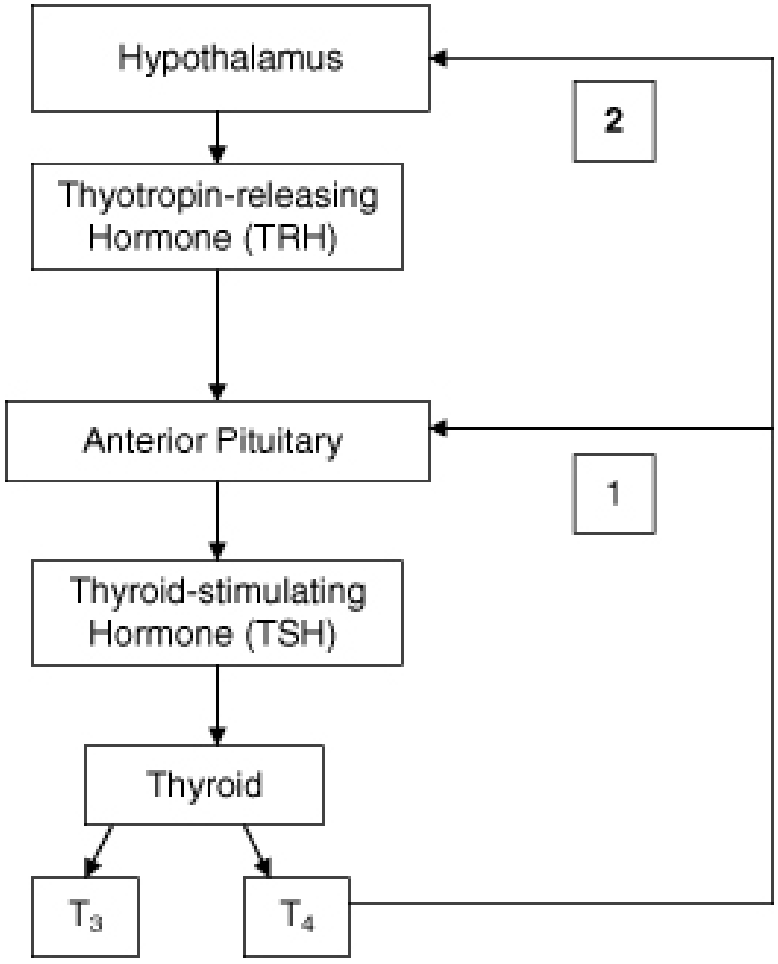

Figure 20.51: Two negative feedback loops exist in the control of thyroid hormone secretion. (1) shows the loop between the TSH-producing cells of the anterior pituitary and the thyroid. Increased levels of T4 and T3 in the blood cause a reduction in TSH secretion. (2) shows that increased levels of T4 and T3 in the blood cause a reduction in TRH secretion.

Positive Feedback

Positive feedback is a reaction in which the system responds in such a way as to speed up the direction of change. Positive feedback mechanisms are not as common as negative feedback mechanisms because they cause an increase in the initial signal, which would tend to knock many systems out of balance. Take for example, the analogy of the home heating system. If this system were to work on a positive feedback loop, the furnace would not switch off when the temperature reached the set point of 21 $^{\circ}$C. Instead, it would keep going and heat the room indefinitely.

An example of a positive feedback mechanism is milk production by a mother for her baby, as shown in **Figure** 20.52. As the baby suckles, nerve messages from the mammary glands cause the hormone prolactin, to be secreted by the mother's pituitary gland. The more the baby suckles, the more prolactin is released, which stimulates further milk production by the mother's mammary glands. In this case, a negative feedback loop would be unhelpful because the more the baby nursed, the less milk would be produced. Another example of a positive feedback loop is the blood-clotting cascade that happens after a blood vessel is cut.

Figure 20.52: Production of breast milk is controlled by a positive feedback mechanism.

Hormone Antagonists

Many hormones work with hormone antagonists to control the concentrations of substances in the body. The hormones have opposite actions on the body and so are called **antagonistic**.

Insulin and glucagon make up an antagonistic hormone pair. The action of insulin is opposite that of glucagon. For example, your blood glucose concentration rises sharply after you eat

food that contains simple carbohydrates, such as the blueberry muffins shown in **Figure** 20.53. The increase in blood glucose level stimulates beta cells in the pancreas to release insulin into blood. In response to signals by insulin most body cells take up glucose, which removes it from the blood, and the blood glucose concentration returns to the set point. Later, you have missed eating lunch, you are hungry and feel a little light-headed. Your blood glucose concentration has dropped below the set point, which causes the release of glucagon from the pancreas. Glucagon causes the release of glucose from liver cells, which increases your blood-glucose concentration. If glucagon did not do its job correctly, your blood glucose concentration would continue to drop, and you would develop hypoglycemia (low blood sugar). This antagonistic relationship between the two hormones helps to maintain the narrow range of blood glucose concentration.

Figure 20.53: Insulin and glucagon work as an antagonistic pair to keep your blood glucose concentration within a narrow range even after you eat food containing carbohydrates, such as a muffin.

The actions of growth hormone releasing hormone (GHRH) are opposed by another hypothalamic hormone, somatostatin, also known as "growth-hormone-inhibiting hormone" (GHIH). Somatostatin and GHRH are secreted alternatively by the hypothalamus, which causes an increase and decrease in the secretion of growth hormone (GH) by the pituitary.

Many endocrine glands also work together as a group to control body processes. The major endocrine glands coordinate the control of various regulatory systems, such as metabolism, osmoregulation, and reproduction. Many individual glands are directly controlled by the nervous system, and all are in some way controlled by the pituitary and hypothalamus. Some of these glands and their hormone products are listed in **Table** 20.10.

Table 20.10: **Coordination of the Endocrine Glands in the Control of Body Systems**

Function	Organ or Glands	Hormones	Nervous System Control
Control of the Endocrine System	Hypothalamus Pituitary Gland	TSH, FSH, LH, GH, prolactin (PRL) Adrenocorticotropic hormone (ACTH)	ANS (sympathetic and parasympathetic nervous system)
Regulation of Metabolism	Thyroid Gland Parathyroid Glands Pancreas Pineal Gland Liver	T_3 and T_4 Parathyroid hormone Insulin Glucagon Melatonin	ANS (sympathetic and parasympathetic nervous system)
Response to Stress	Adrenal Glands	Epinepherine, norepinepherine, cortisol	ANS (sympathetic nervous system)
Reproduction	Gonads (ovaries, testes)	Androgens (testosterone), estrogens, progestins (progesterone)	ANS (parasympathetic nervous system)
Osmoregulation	Adrenal Glands Kidneys Liver	Aldosterone ADH Angiotensin	ANS (sympathetic and parasympathetic nervous system)

Table 20.10: (continued)

Function	Organ or Glands	Hormones	Nervous System Control

Homeostatic Imbalance: Endocrine System Disorders

Diseases of the endocrine system are common, and include diseases such as diabetes, thyroid disease, and obesity. An endocrine disease is usually characterized by hyposecretion or hypersecretion of hormones and an inappropriate response to hormone signaling by cells.

Cancer can occur in endocrine glands, such as the thyroid, and some hormones are involved in signaling distant cancer cells to multiply. For example, the estrogen receptor has been shown to be involved in certain types of breast cancers.

Hyposecretion

Hyposecretion is the production no hormone or too little of a hormone. It can be caused by the destruction of hormone-secreting cells, such as in Type 1 diabetes, or by a deficiency in a nutrient that is important for hormone synthesis. Hyposecretion can be treated with hormone-replacement therapies. Type 1 diabetes is an autoimmune disease that results in the destruction of the insulin-producing beta cells of the pancreas. A person with Type 1 diabetes needs insulin replacement therapy, usually by injection or insulin pump, in order to stay alive. An insulin pump is shown in **Figure** 20.54.

Diabetes insipidus is characterized by excretion of large amounts of very dilute urine, even if liquid intake is reduced. It is caused by an inability of the kidney to concentrate urine due to a lack of antidiuretic hormone (ADH) also called vasopressin, or by an insensitivity of the kidneys to that hormone. Blood glucose levels are not affected in diabetes insipidus.

Growth hormone deficiency is caused by a lack of GH production by the pituitary. GH deficiency affects bone growth development, and people with growth hormone deficiency tend to have, among other things, low bone density and small stature, a condition called pituitary dwarfism. GH deficiency is treated by growth hormone replacement.

Hypothyroidism is the state in which not enough thyroid hormones are made. Thyroiditis is an autoimmune disease where the body's own antibodies attack the cells of the thyroid and destroy it. Thyroid hormones play an important role in brain development during fetal growth. Cells of the brain are a major target for the T3 and T4 hormones. As a result, hypothyroidism in children, either due to a thyroid problem from birth or a lack of iodine in the diet, is a major cause of physical and mental growth impairment in developing countries. In fact, iodine deficiency disorders are the single most common cause of preventable mental retardation and brain damage in the world.

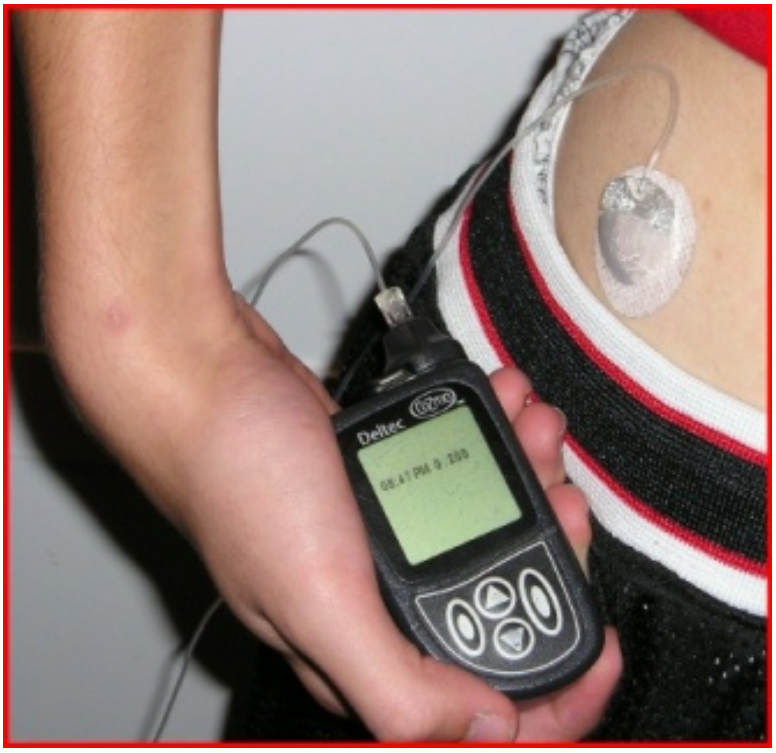

Figure 20.54: In the treatment of Type 1 diabetes, an insulin pump is an alternative to multiple daily injections of insulin. The pump is usually used along with the monitoring of blood glucose concentration and carbohydrate intake.

Figure 20.55: There are many causes of goiter, but the most common is the world is iodine deficiency. Today, iodine deficiency remains mostly a problem in poorer countries which lack the means to add iodine to foods. Iodized salt has helped reduce the amount of iodine deficiency in the developed world. Governments of some countries add iodine to cattle feed to ensure that dairy foods will contain iodine.

Hypersecretion

Hypersecretion of a hormone happens when the body produces too much of a hormone. A hormone can be hypersecreted if the gland develops a tumor and grows out of control, or if the gland is signaled to produce too much of a hormone.

Hyperthyroidism is the result of excess thyroid hormone production, which causes an overactive metabolism and increased speed of all the body's processes. Hyperthyroidism is the most common cause of goiter in the developed world, shown in **Figure** 20.55.

Hypersecretion of growth hormone causes acromegaly. A common cause of acromegaly is a benign tumor of the pituitary glands that releases too much GH. In some cases, acromegaly is also caused by overproduction of the hypothalamus hormone growth hormone release hormone (GHRH). Acromegaly most commonly affects middle-aged adults and can result in serious illness and premature death. Symptoms include enlarged hands and feet, protruding brow and chin, and enlarged internal organs. However, the disease is hard to diagnose in the early stages and is frequently missed for many years due to its slow progression. If the pituitary produced too much GH during childhood, the person will be taller than normal, a condition called pituitary gigantism. Pituitary gigantism is very rare, and some of the tallest people on record had this condition.

Hormone Insensitivity: Type 2 Diabetes

In some cases, the body makes enough hormones, but body cells do not respond. This can be due to missing or defective hormone receptors, or the body cells become resistant to normal concentration of the hormone, and do not respond to it.

Type 2 diabetes is characterized by hyperglycemia (high blood glucose concentrations), body cells that do not respond to normal amounts of insulin (insulin resistance), and the resulting inability of the pancreas to produce enough insulin. Insulin resistance in cells results in high amounts of free fatty acids and glucose in the blood. High plasma levels of insulin and glucose due to insulin resistance often lead to metabolic syndrome and Type 2 diabetes. Type 2 diabetes can be controlled by improving the diet, increasing levels of activity, and sometimes medication.

Gestational diabetes is a form of diabetes that affects pregnant women. There is no known single cause, but it's believed that the hormones produced during pregnancy reduce the ability of the cells in the pregnant woman's body to respond to insulin, which results in high blood glucose concentrations.

Hormones as Medicines

Many hormones and molecules like them are used as medicines. The most common type of therapy is called **hormone-replacement therapy**. The most commonly-prescribed hormones are estrogens and synthetic progesterone (as methods of hormonal contraception and as HRT therapy for post-menopausal women), thyroxine (as levothyroxine, for hypothyroidism) and corticosteroids (for autoimmune diseases and several respiratory disorders). Progestin, a synthetic progesterone, is also used to prolong pregnancy in women who have experienced a miscarriage due to a premature drop in progesterone levels. Hydrocortisone is a synthetic form of cortisol that is used to treat allergies and inflammation as well as cortisol production deficiencies. Hydrocortisone cream is a common over-the-counter medication for the topical treatment of rash. Insulin is used by many people with diabetes.

Epinephrine

Because of its anti inflammatory effect on the immune system, epinephrine is used to treat anaphylaxis. Anaphylaxis is a sudden and severe allergic reaction that involves the entire body. After an initial exposure to a substance like a certain food (such as peanuts), or bee sting, a person's immune system can becomes sensitized to that substance, which is called an **allergen**. Upon second exposure, an allergic reaction occurs.

Figure 20.56: An EpiPen® epinephrine autoinjector. Auto injectors like this one can help save a person's life during an anaphylactic reaction.

Histamine and other substances that are released by body cells cause the blood vessels to dilate, which lowers blood pressure, and fluid to leak from the bloodstream into the tissues, which lowers the blood volume. The release of histamine causes the face and tongue to swell. Swelling of the lining of the throat can lead to breathing difficulties. The hormone epinephrine causes blood vessels to constrict which reduces swelling and causes blood pressure to increase. Epinephrine is used as a medicine in auto-injectors, shown in **Figure** 20.56, which a person can use themselves should they have an anaphylactic reaction.

Anabolic Androgenic Steroids

Synthetic androgens, in the form of anabolic androgenic steroids (anabolic steroids), have many medical uses. It is used to stimulate bone growth and appetite, induce puberty in boys,

and treat muscle-wasting conditions in patients that have diseases such as cancer and AIDS. In general, androgens, including testosterone, promote protein synthesis and the growth of muscle tissue and other tissues that have androgen receptors. Androgens also block the effects of the stress hormone cortisol on muscle tissue, so the breakdown of muscle is greatly reduced.

Figure 20.57: Athletes involved in sports that emphasize strength, weight, and shape may feel pressure to take anabolic steroids, however, the majority of school athletes do not take them.

Anabolic Steroid Abuse

As a result of their muscle-building action, anabolic steroids are used in sport and bodybuilding to increase muscle size and strength, to gain a competitive edge or to assist in recovery from injury. Steroids used to gain competitive advantage are forbidden by the rules of the governing bodies of many sports. Serious health risks can be produced by long-term use or excessive doses of anabolic steroids. Most of these side effects are dose dependent, the most common being an increase in low density lipoprotein (bad cholesterol), and a decrease in good high density lipoprotein (good cholesterol). Anabolic steroids also increase the risk of cardiovascular disease in men with high risk of bad cholesterol. Acne is fairly common among anabolic steroid users, mostly due to increases in testosterone which stimulates the sebaceous glands to produce more oil. High doses of anabolic steroids have been linked to liver damage.

Teenagers, particularly boys, who take anabolic steroids, are more likely to be involved in sports that emphasize weight and shape, (such as football or wrestling, which is shown in **Figure** 20.57). Such teens also have higher rates of disordered eating, drug abuse, and generally have poorer attitudes towards health. Severe side effects can occur if a teenager

uses anabolic steroids. For example, the steroids may prematurely stop the lengthening of bones, resulting in stunted growth. Other effects include, but are not limited to, accelerated bone maturation, increased acne outbreaks, and premature sexual development.

In addition to dangerous side effects of the steroids themselves, dangerous drug-taking habits that have been reported by abusers include: unsafe injection practices such as reusing needles, sharing needles, and sharing multidose vials. A common practice among anabolic steroid abusers is self–medicating with other hormones such as growth hormone and insulin, which in itself can lead to serious health consequences. Testosterone and other anabolic steroids are classified as a controlled substance in the United States (US), Canada, the United Kingdom (UK), Australia, Argentina, and Brazil.

Lesson Summary

- The endocrine system is a system of organs that release hormones into the blood. Unlike the nervous system whose action helps the body react immediately to change, the endocrine system controls changes that happen to the body over a long period of time.
- Hormones are made and secreted by cells in endocrine glands. The body produces many different hormones, but each hormone is very specific for its target cells.
- The hypothalamus links the nervous system to the endocrine system by the pituitary gland. The pituitary gland secretes hormones that regulate homeostasis and also secretes hormones that stimulate other endocrine glands. Together the two glands serve as the major control centers of the endocrine system.
- The ovaries of females and the testes of males are the gamete producing organs, or gonads. In addition to producing gametes, an exocrine action, the gonads are endocrine glands that produce steroid sex hormones.
- The rate of hormone production and secretion is often regulated by homeostatic feedback control mechanisms, and the effect of hormones is controlled by hormone antagonists. In these ways, the concentration of hormones and their products is kept within a narrow range so as to maintain life.
- A feedback control mechanism, or a feedback loop, is a signaling system in which a product or effect of the system controls an earlier part of the system, either by shutting the process down or speeding it up.
- Diseases of the endocrine system are common, and include diseases such as diabetes, thyroid disease, and obesity. Many hormones and hormone-like molecules are used as medicines. The most common type of therapy is called hormone-replacement therapy.

Review Questions

1. How does a hormone initially activate a target cell?
2. What is the main difference between the locations of the receptors for amino acid-based

hormones and steroid-based hormones?
3. List five main endocrine glands, and identify their locations.
4. Name the two glands that control the nervous system.
5. Name three hormones that are involved in the stress response and identify their function.
6. Outline the role of the parathyroid glands in regulation of blood calcium levels.
7. What hormone is secreted by the pineal gland, and what is the function of the hormone?
8. How do feedback mechanisms help maintain homeostasis?
9. How does negative feedback differ from positive feedback?
10. Identify an antagonistic pair of hormones and describe their action.
11. Why do you think the pituitary has two lobes?
12. What is the purpose of hormone replacement therapy?
13. Why might a problem with the pituitary gland affect many different parts of the body?
14. Your friend says that he's pretty sure that the adrenal medulla is controlled by hormones from the pituitary. Do you agree? Explain your answer.
15. Outline the feedback mechanism involved in glucose metabolism. Is this feedback mechanism positive or negative?
16. Positive feedback mechanisms are harmful to the body. Do you agree with this statement? Explain your answer.
17. Goiter is a swelling of the thyroid gland, which is commonly caused by a lack of iodine in the diet. Why do you think a lack of iodine causes the thyroid to swell?
18. Use the image of the feedback mechanisms to answer the two questions that follow.
19. Identify four hormones involved in these feedback mechanisms.

Further Reading / Supplemental Links

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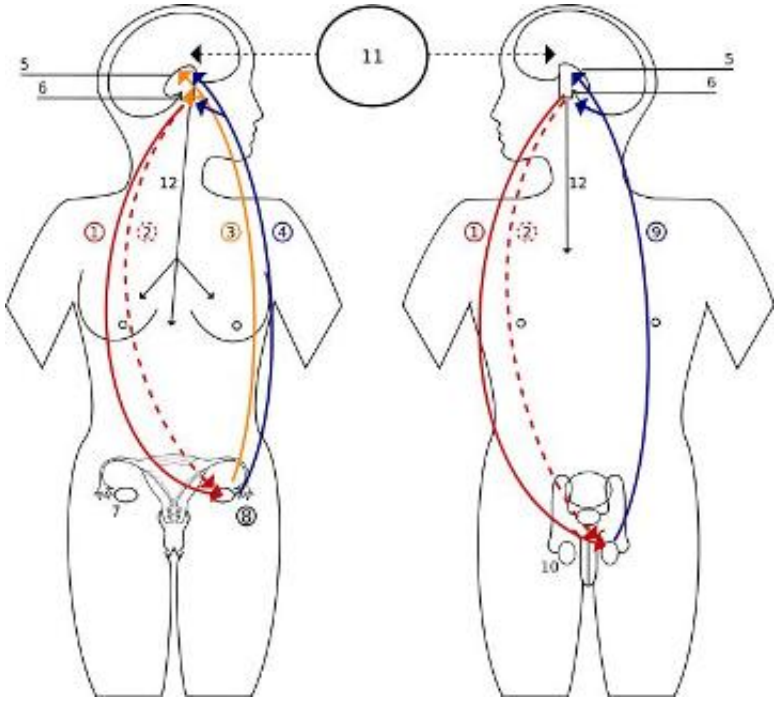

Figure 20.58: Identify three endocrine glands are involved in the feedback mechanisms shown in the figure.

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Vocabulary

amino acid-based hormones Hormones made of amino acids; not fat-soluble and therefore cannot diffuse through the plasma membrane of their target cell; usually bind to receptors that are found on the cell membrane.

antagonistic Hormones that have opposite actions on the body, such as insulin and glucagons.

cholesterol-based hormones Hormones made of lipids such as phospholipids and cholesterol; also called steroid hormones; are fat soluble and are able to diffuse through the

plasma membrane; bind to receptors that are found within the cell cytosol and nucleus.

circadian rhythm A roughly-24-hour cycle in the biological processes carried out within organisms, including plants, animals, fungi and certain bacteria.

cortisol A steroid hormone produced by the adrenal glands; often called the "stress hormone" as it is involved in the body's response to stress; increases blood pressure, blood sugar levels and has an immunosuppressive action.

direct gene activation A system in which a fat-soluble hormone diffuses across the membrane and binds to the receptor within the cytosol or nucleus. The hormone-receptor complex then acts as a transcription factor that affects gene expression.

endocrine glands Ductless organs that make and secrete hormones directly into the blood or the fluid surrounding a cell rather than through a duct.

endocrine system A system of organs that releases chemical message molecules, called hormones, into the blood.

exocrine glands Organs that secrete their products into ducts (they are duct glands); do not secrete hormones; secrete products such as water, mucus, enzymes, and other proteins through ducts to specific locations inside and outside the body.

feedback control mechanism A signaling system in which a product or effect of the system controls an earlier part of the system, either by shutting the process down or speeding it up; also known as a feedback loop.

glucagon An important hormone involved in carbohydrate metabolism; released when the glucose level in the blood is low which causes the liver to change stored glycogen into glucose and release it into the bloodstream.

gonads The gamete producing organs; the ovaries of females and the testes of males.

hormone-like substances Refers to a group of signaling molecules that are derived from certain types of fatty acids and proteins.

hormones Chemical messenger molecules that are made by cells in one part of the body and cause changes in cells in another part of the body.

hypersecretion The production of too much of a hormone.

hyposecretion The production of no hormone or too little of a hormone.

hypothalamus Area of the brain that coordinates many seasonal and circadian rhythms, complex homeostatic mechanisms, and the autonomic nervous system (ANS).

islets of Langerhans Areas of the pancreas with groupings of endocrine cells; produce the amino acid-based hormones insulin, glucagon, and somatostatin.

negative feedback A reaction in which the system responds in such a way as to reverse the direction of change.

neuropeptides Hormone-like substance; signaling peptides found in nervous tissue.

positive feedback A reaction in which the system responds in such a way as to speed up the direction of change.

prostaglandins Hormone-like substance made from essential fatty acids; produced by most cells in the body; have many different effects such as causing constriction or dilation of blood vessels but they are all are localized within the target cells and tissues.

puberty The process of physical changes during which the sex organs mature and a person become capable of reproducing.

second messenger system A system in which a water-soluble hormone molecule does not enter the cell, instead it binds to the membrane-bound receptor molecule, which triggers changes within the cell. These changes are activated by second messenger molecules.

sex hormones Hormones that are responsible for the secondary sex characteristics that develop at puberty.

signal transduction pathway Process initiated by the binding of a hormone to its receptor; a process of molecular changes that turns the hormone's extracellular signal into an intracellular response.

target cell The cell on which a hormone has an effect; has receptor proteins that are specific to the hormone.

Points to Consider

- Think about some of the problems people may have to their muscular systems if their nervous system is not functioning correctly.
- Propose what would happen if the hypothalamus did not produce ADH.
- Why are negative feedback loops more common than positive feedback loops?

Image Sources

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Chapter 21

Skeletal, Muscular, and Integumentary Systems

21.1 Lesson 21.1: Skeletal System

Lesson Objectives

- Identify the functions and structure of bones.
- Differentiate between the axial skeleton and appendicular skeleton.
- Distinguish between spongy bone and compact bone.
- Outline the process of osteogenesis (bone formation), and how bones grow.
- Classify bones based on their shape.
- Identify three types of joints that are in the body, and give an example of each.
- Identify three disorders that result from homeostatic imbalances of bones or the skeleton.

Introduction

How important is your skeleton? Can you imagine what you would look like without it?

You would be a wobbly pile of muscle and internal organs, maybe a little similar to the slug in **Figure** 21.1. Not that you would really be able to see yourself anyway, due to the folds of skin that would droop over your eyes because of your lack of skull bones. You could push the skin out of the way, if you could only move your arms!

Figure 21.1: Banana slugs (spp.), unlike you, can live just fine without a bony skeleton. They can do so because they are relatively small and their food source (vegetation) is plentiful and tends not to run away from them. Slugs move by causing a wave-like motion in their foot, (the ventral (bottom) area of the slug that is in contact with the ground). Slugs and other gastropods also live in environments very different to humans' environments. Just think of how a bony skeleton would be of limited use to a slug whose lifetime is spent under a log munching on rotting leaf litter.

The Skeleton

Humans are vertebrates, which are animals that have a vertebral column, or backbone. Invertebrates, like the banana slug in **Figure** 21.1, do not have a vertebral column, and use a different mechanism than vertebrates to move about. The sturdy internal framework of bones and cartilage that is found inside vertebrates, including humans, is called an **endoskeleton**. The adult human skeleton consists of approximately 206 bones, some of which are named in **Figure** 21.2. Cartilage, another component of the skeleton can also be seen in **Figure** 21.2. **Cartilage** is a type of dense connective tissue that is made of tough protein fibers. The function of cartilage in the adult skeleton is to provide smooth surfaces for the movement of bones at a joint. A **ligament** is a band of tough, fibrous tissue that connects bones together. Ligaments are not very elastic and some even prevent the movement of certain bones.

The skeletons of babies and children have many more bones and more cartilage than adults have. As a child grows, these "extra" bones, such as the bones of the skull (cranium), and the sacrum (tailbone) fuse together, and cartilage gradually hardens to become bone tissue.

The bones of the skeleton can be grouped in two divisions: the axial skeleton and appendicular skeleton. The **axial skeleton** includes the bones of the head, vertebral column, ribs and sternum, in the left portion of **Figure** 21.3. There are 80 bones in the axial skeleton. The **appendicular skeleton** includes the bones of the limbs (arms and legs) along with the scapula and the pelvis, and is shown at right in **Figure** 21.3. There are approximately 126 bones in the appendicular skeleton. Limbs are connected to the rest of the skeleton by collections of bones called girdles. The pectoral girdle consists of the clavicle (collar bone) and scapula (shoulder blade). The pelvic girdle consists of two pelvic bones (hipbones) that form the pelvic girdle. The vertebral column attaches to the top of the pelvis; the femur of each leg attaches to the bottom. The humerus is joined to the pectoral girdle at a joint and is held in place by muscles and ligaments.

Function and Structure of Bones

Many people think of bones as dry, dead, and brittle, which is what you might think if you saw a preserved skeleton in a museum. The association of bones with death is illustrated by the sweets shown in **Figure** 21.4. This is a common association because the calcium-rich bone tissue of a vertebrate is the last to decompose after the organism dies. However, the bones in your body are very much alive. They contain many tough protein fibers, are crisscrossed by blood vessels, and certain parts of your bones are metabolically active. Preserved laboratory skeletons are cleaned with chemicals that remove all organic matter from the bones, which leaves only the calcium-rich mineralized (hardened) bone tissue behind.

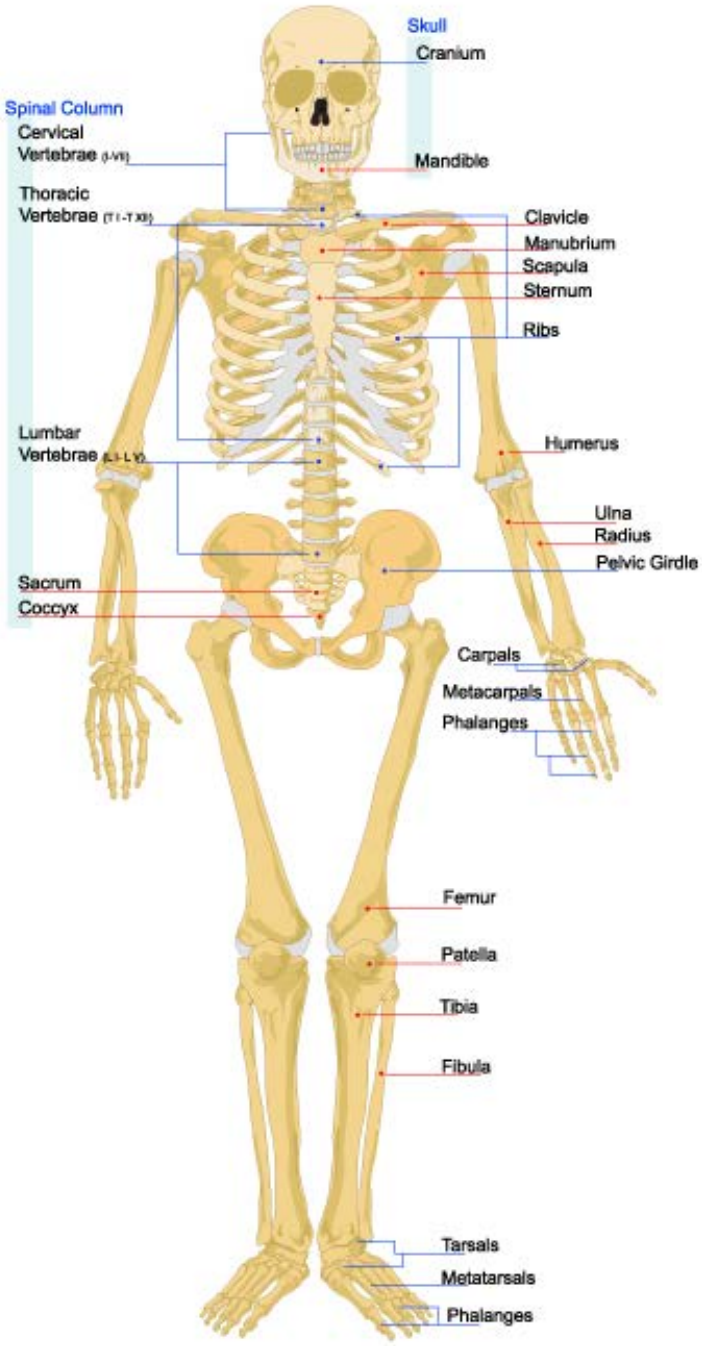

Figure 21.2: The skeleton is the bone and cartilage scaffolding that supports the body, and allows it to move. Bones act as attachment points for the muscles and tendons that move the body. Bones are also important for protection. For example, your skull bones (cranium) protect your brain, and your ribcage protects your heart and lungs. Cartilage is the light-gray material that is found between some of the bones and also between the ribcage and sternum.

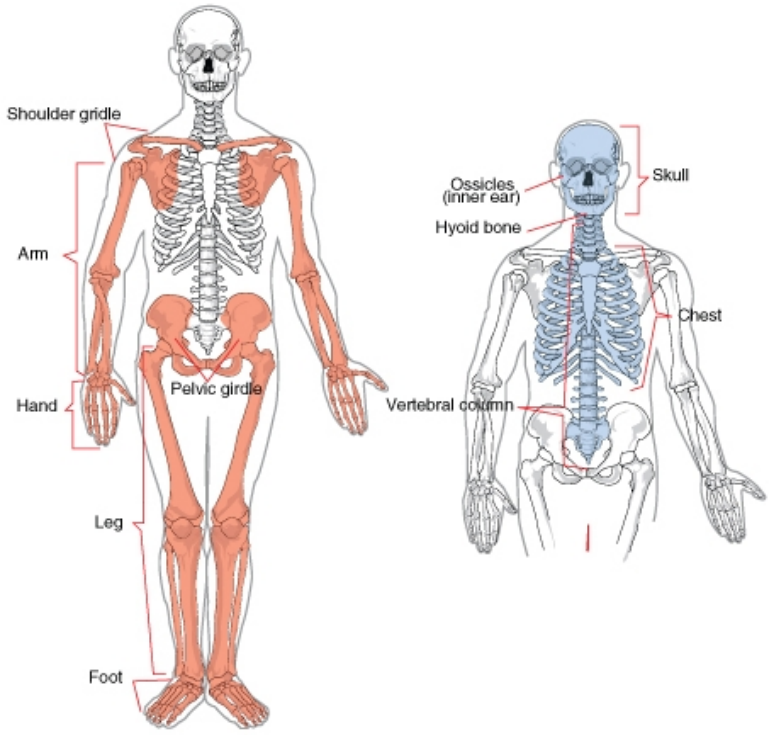

Figure 21.3: The two divisions of the human skeleton. The bones of the axial skeleton are blue, and the bones of the appendicular skeleton are pink.

Figure 21.4: Sugar skulls made to celebrate Dia de Los Muertos (Day of the Dead), a time (the 1 and 2 of November) during which the people of Mexico and some Latin American countries celebrate and honor the lives of the deceased, and celebrate the continuation of life.

Functions of Bones

As you read earlier in this lesson, your skeletal system is important for the proper functioning of your body. In addition to giving shape and form to the body, bones have many important functions.

The main functions of bones are:

- Structural Support of the Body: The skeleton supports the body against the pull of gravity. The large bones of the lower limbs support the trunk when standing.
- Protection of Internal Organs: The skeleton provides a rigid frame work that supports and protects the soft organs of the body. The fused bones of the cranium surround the brain to make it less vulnerable to injury. Vertebrae surround and protect the spinal cord and bones of the rib cage help protect the heart and lungs.
- Attachment of the Muscles: The skeleton provides attachment surfaces for muscles and tendons which together enable movement of the body.
- Movement of the Body: Bones work together with muscles as simple mechanical lever systems to produce body movement.
- Production of Blood Cells: The formation of blood cells takes place mostly in the interior (marrow) of certain types of bones.
- Storage of Minerals: Bones contain more calcium than any other organ in the form of calcium salts such as calcium phosphate. Calcium is released by the bones when blood

levels of calcium drop too low. Phosphorus is also stored in bones.

Structure of Bones

Although bones vary greatly in size and shape, they all have certain structural similarities. Bones are organs.Recall that organs are made up of two or more types of tissues. The two main types of bone tissue are compact bone and spongy bone. **Compact bone** makes up the dense outer layer of bones. **Spongy bone** is lighter and less dense than compact bone, and is found toward the center of the bone. **Periosteum** (from *peri* = around, *osteo* = bone),is the tough, shiny, white membrane that covers all surfaces of bones except at the joint surfaces. Periosteum is composed of a layer of fibrous connective tissue and a layer of bone forming cells. These structures can be seen in **Figure** 21.5.

Compact Bone

Just below the periosteum is the hard layer of compact bone tissue. It is so called due to its high density, and it accounts for about 80% of the total bone mass of an adult skeleton. Compact bone is extremely hard, and is made up of many cylinder-shaped units called **osteons**, or Haversian systems. Osteons act like strong pillars within the bone to give the bone strength and allow it to bear the weight of the attached muscles and withstand the stresses of movement. As you can see in **Figure** 21.6, osteons are made up of rings of calcium salts and collagen fibers, called bone matrix. **Bone matrix** is a mixture of calcium salts, such as calcium phosphate and calcium hydroxide, and collagen fibers (a type of protein) which form hollow tubes that look similar to the rings on a tree. Each of these matrix tubes is a lamella, which means "thin plate" (plural: lamellae). The calcium salts form crystals that give bones great strength, but the crystals do not bend easily, and tend to shatter if stressed. Collagen fibers are tough and flexible. All collagen fibers within a single lamella are lined up in the same direction, which gives each lamella great strength. Overall, the protein-calcium crystal combination in the matrix allows bones to bend and twist without breaking easily. The collagen fibers also act as a scaffold for the laying down of new calcium salts.

In the center of each osteon is a **Haversian canal**. The canal serves as a passageway for blood vessels and nerves. Within each osteon, many bone cells called osteocytes are located. Osteocytes are found in little pockets called lacunae that are sandwiched between layers of bone matrix. You can see lamellae and osteocytes in their lacunae in **Figure 7b**. **Osteocytes** are responsible for monitoring the protein and mineral content of the bone and they direct the release of calcium into the blood and the uptake up of calcium salts into the bone. Other bone cells, called **osteoblasts** secrete the organic content of matrix, and are responsible for the growth of new bone. Osteoblasts are found near the surface of bones. **Osteoclasts** are bone cells that remove calcium salts from bone matrix. These bone cells will be discussed in further detail later in this lesson. In the meantime, **Table** 21.1 describes

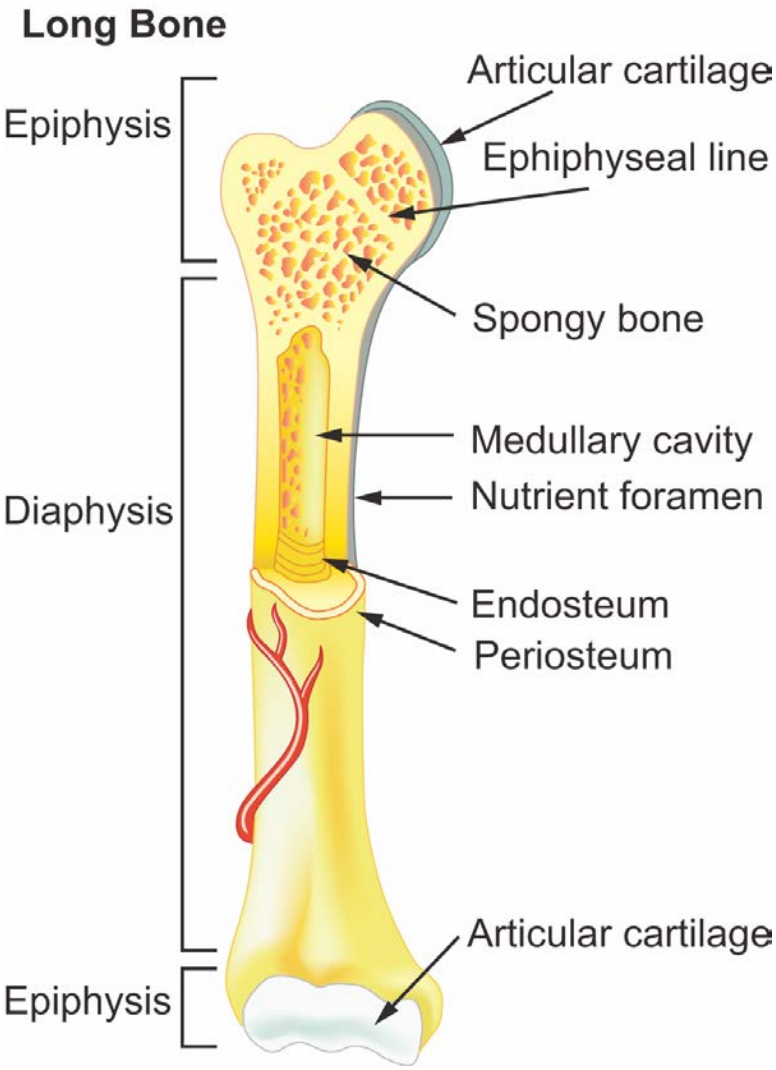

Figure 21.5: Structure of a typical bone. The components that make up bones can be seen here. Compact bone is the dense material that makes up the outer ring of the bone. Most bones of the limbs are long bones, including the bones of the fingers. The classification of "long bone" refers to the shape of the bone rather than to the size.

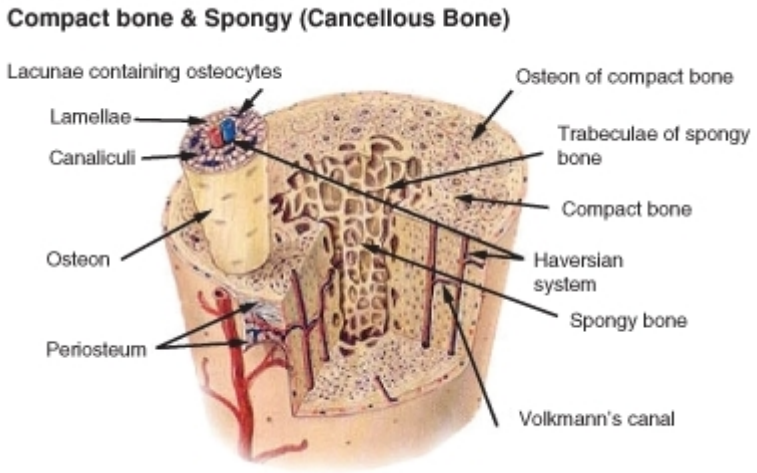

Figure 21.6: The internal structure of a bone. Both compact and spongy bone can be seen.

some of the different structures and functions of bones.

Table 21.1: **The Structure of Bones**

	Function	Location
Osteons (also known as Haversian systems)	Act like pillars to give bone strength	Compact bone
Bone matrix	A mixture of calcium salts and collagen fibers which form hollow tubes that look similar to the rings on a tree	Compact bone, spongy bone
Lamella	Layers of bone matrix in which collagen fibers point in the opposite direction to the fibers of the lamellae to each side, offers great strength and flexibility	Are the "tree rings" of osteons
Lacunae	Location of osteocytes	Between lamellae of bone matrix
Osteocytes	Monitor the protein and mineral content of bone and direct the release of calcium into the blood; control the uptake up of calcium salts into the bone	Within lacunae of osteons

Table 21.1: (continued)

	Function	Location
Osteoblasts	Bone-forming cell; secretes organic part of matrix (collagen)	Found near the surface of bones
Osteoclasts	Responsible for the breakdown of matrix and release of calcium salts into the blood.	Bone surfaces
Chondrocyte	Cartilage-forming cell	
Periosteum	Contains pain receptors and is sensitive to pressure or stress; provides nourishment through a good the blood supply; provides an attachment for muscles and tendons	
Collagen fibers	Tough protein fibers that give bones flexibility and prevent shattering.	
Calcium salts	Form crystals that give bones great strength.	

Spongy Bone

Spongy bone occurs at the ends of long bones and is less dense than compact bone. The term "spongy" refers only to the appearance of the bone, as spongy bone is quite strong. The lamellae of spongy bone form an open, porous network of bony branches, or beams called trabiculae, that give the bone strength and make the bone lighter. It also allows room for blood vessels and bone marrow. Spongy bone does not have osteons, instead nutrients reach the osteocytes of spongy bone by diffusion through tiny openings in the surface of the spongy bone. Spongy bone makes up the bulk of the interior of most bones, including the vertebrae.

Bone Marrow

Many bones also contain a soft connective tissue called **bone marrow**. There are two types of bone marrow: red marrow and yellow marrow. Red marrow produces red blood cells, platelets, and most of the white blood cells for the body. Yellow marrow produces white

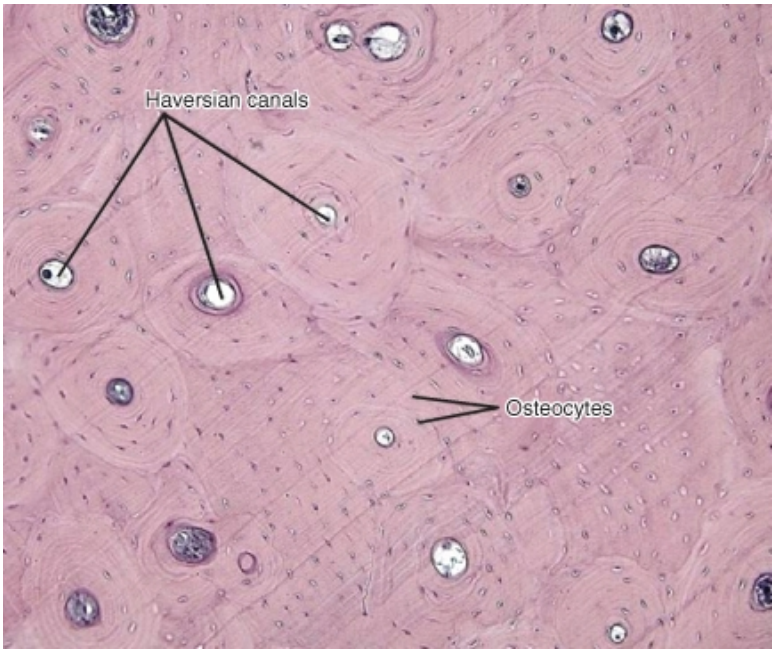

Figure 21.7: The location of Haversian canals and osteocytes in osteons of compact bone.

blood cells. The color of yellow marrow is due to the high number of fat cells it contains. Both types of bone marrow contain numerous blood vessels and capillaries. In newborns, bones contain only red marrow. As the child ages, red marrow is mostly replaced by yellow marrow. In adults, red marrow is mostly found in the flat bones of the skull, the ribs, the vertebrae and pelvic bones. It is also found between the spongy bone at the very top of the femur and the humerus.

Periosteum

The outer surfaces of bones—except where they make contact with other bones at joints—are covered by periosteum. Periosteum has a tough, external fibrous layer, and an internal layer that contains osteoblasts (the bone-growing cells). The periosteum is richly supplied with blood, lymph and nociceptors, which make it very sensitive to manipulation (recall that nociceptors are pain receptors that are also found in the skin and skeletal muscle). Periosteum provides nourishment to the bone through a rich blood supply. The periosteum is connected to the bone by strong collagen fibers called Sharpey's fibres, which extend into the outer lamellae of the compact bone.

Bone Shapes

The four main types of bones are long, short, flat, and irregular. The classification of a bone as being long, short, flat, or irregular is based on the shape of the bone rather than the size of the bone. For example, both small and large bones can be classified as long bones. There are also some bones that are embedded in tendons, these bones tend to be oval-shaped and are called sesamoid bones.

- **Long Bones:** Bones that are longer than they are wide are called long bones. They consist of a long shaft with two bulky ends. Long bones are primarily made up of compact bone but may also have a large amount of spongy bone at both ends. Long bones include bones of the thigh (femur), leg (tibia and fibula), arm (humerus), forearm (ulna and radius), and fingers (phalanges). The classification refers to shape rather than the size.
- **Short Bones:** Short bones are roughly cube-shaped, and have only a thin layer of compact bone surrounding a spongy interior. The bones of the wrist (carpals) and ankle (tarsals) are short bones, as are the sesamoid bones (see below).
- **Sesamoid Bones:** Sesamoid bones are embedded in tendons. Since they act to hold the tendon further away from the joint, the angle of the tendon is increased and thus the force of the muscle is increased. An example of a sesamoid bone is the patella (kneecap).
- **Flat Bones:** Flat bones are thin and generally curved, with two parallel layers of compact bones sandwiching a layer of spongy bone. Most of the bones of the skull (cranium) are flat bones, as is the sternum (breastbone).
- **Irregular Bones:** Irregular bones are bones that do not fit into the above categories. They consist of thin layers of compact bone surrounding a spongy interior. As implied by the name, their shapes are irregular and complicated. The vertebrae and pelvis are irregular bones.

All bones have surface markings and characteristics that make a specific bone unique. There are holes, depressions, smooth facets, lines, projections and other markings. These usually represent passageways for vessels and nerves, points of articulation with other bones or points of attachment for tendons and ligaments.

Cellular Structure of Bone

When blood calcium levels decrease below normal, calcium is released from the bones so that there will be an adequate supply for metabolic needs. When blood calcium levels are increased, the excess calcium is stored in the bone matrix. The dynamic process of releasing and storing calcium goes on almost continuously, and is carried out by different bone cells.

There are several types of bone cells.

- **Osteoblasts** are bone-forming cells which are located on the inner and outer surfaces of bones. They make a collagen-rich protein mixture (called osteoid), which mineralizes to become bone matrix. Osteoblasts are immature bone cells. Osteoblasts that become trapped in the bone matrix differentiate into osteocytes. The osteocytes stop making osteoid and instead direct the release of calcium from the bones and the uptake of calcium from the blood.
- **Osteocytes** originate from osteoblasts which have migrated into and become trapped and surrounded by bone matrix which they themselves produce. The spaces which they occupy are known as lacunae. Osteocytes are star-shaped, and they have many processes which reach out to meet osteoblasts probably for the purposes of communication. Their functions include matrix maintenance and calcium homeostasis. They are mature bone cells. Refer to **Figure** 21.7 for the location of osteocytes.
- **Osteoclasts** are the cells responsible for bone **resorption**, which is the remodeling of bone to reduce its volume (see below). Osteoclasts are large cells with many nuclei, and are located on bone surfaces. They secrete acids which dissolve the calcium salts of the matrix, releasing them into the blood stream. This causes the calcium and phosphate concentration of the blood to increase. Osteoclasts constantly remove minerals from the bone, and osteoblasts constantly produce matrix that binds minerals into the bone, so both of these cells are important in calcium homeostasis.

Bone Cells and Calcium Homeostasis

Remodeling or bone turnover is the process of resorption of minerals followed by replacement by bone matrix which causes little overall change in the shape of the bone. This process occurs throughout a person's life. Osteoblasts and osteoclasts communicate with each other for this purpose. The purpose of remodeling is to regulate calcium homeostasis, repair micro-damaged bones (from everyday stress), and also to shape the skeleton during skeletal growth.

The process of bone resorption by the osteoclasts releases stored calcium into the systemic circulation and is an important process in regulating calcium balance. As bone formation actively fixes circulating calcium in its mineral form, removing it from the bloodstream, resorption actively unfixes it thereby increasing circulating calcium levels. These processes occur in tandem at site-specific locations.

Development of Bones

The terms osteogenesis and ossification are often used to indicate the process of bone formation. The skeleton begins to form early in fetal development. By the end of the eighth week after conception, the skeletal pattern is formed by cartilage and connective tissue membranes. At this point, ossification begins.

Early in fetal development, the skeleton is made of cartilage. Cartilage is a type of dense connective tissue that is composed of collagen fibers and/or elastin fibers, and cells called chondrocytes which are all set in a gel-like substance called matrix. Cartilage does not contain any blood vessels so nutrients diffuse through the matrix to the chondrocytes. Cartilage serves several functions, including providing a framework upon which bone deposition can begin and supplying smooth surfaces for the movement of bones at a joint, such as the cartilage shown in **Figure** 21.8.

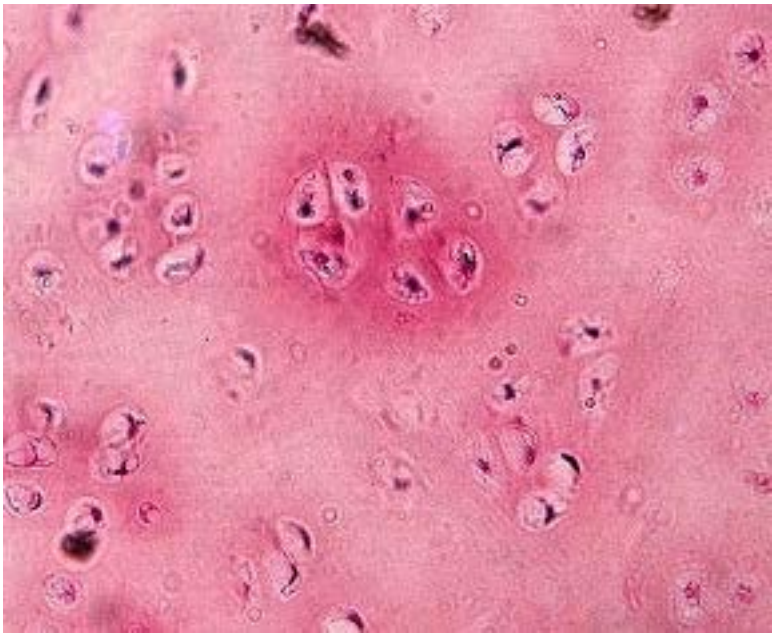

Figure 21.8: A micrograph of the structure of hyaline cartilage, the type of cartilage that is found in the fetal skeleton and at the ends of mature bones.

The bones of the body gradually form and harden throughout the remaining gestation period and for years after birth in a process called **endochondrial ossification**. However, not all parts of the fetal cartilage are replaced by bone, cartilage remains in many places in the body including the joints, the rib cage, the ear, the tip of the nose, the bronchial tubes and the little discs between the vertebrae.

Endochondral Ossification

Endochondral ossification is the process of replacing cartilage with bony tissue, as shown in **Figure** 21.9. Most of the bones of the skeleton are formed in this way. During the third month after conception, blood vessels form and grow into the cartilage, and transport osteoblasts and stem cells into the interior which change the cartilage into bone tissue. The osteoblasts form a bone collar of compact bone around the central shaft (diaphysis) of the bone. Osteoclasts remove material from the center of the bone, and form the central cavity

of the long bones. Ossification continues from the center of the bone toward the ends of the bones.

The cartilage at the ends of long bones (the epiphyses) continues to grow so the developing bone increases in length. Later, usually after birth, secondary ossification centers form in the epiphyses, as shown in **Figure** 21.9. Ossification in the epiphyses is similar to that in the center of the bone except that the spongy bone is kept instead of being broken down to form a cavity. When secondary ossification is complete, the cartilage is totally replaced by bone except in two areas. A region of cartilage remains over the surface of the epiphysis as articular cartilage and another area of cartilage remains inside the bone at either end. This area is called the **epiphyseal plate** or growth region.

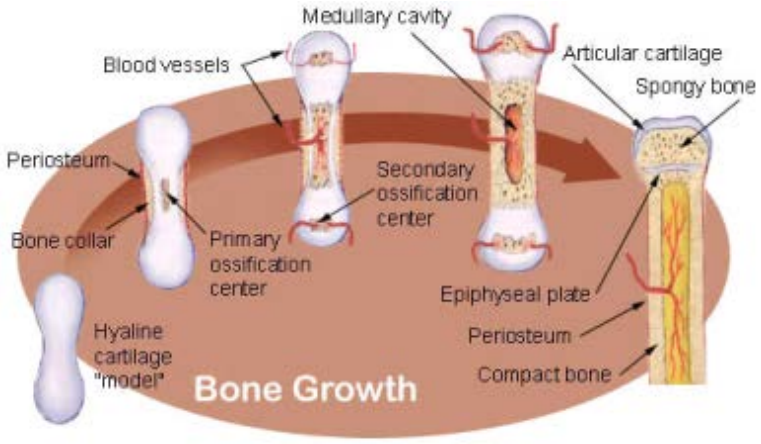

Figure 21.9: The process of endochondrial ossification which happens when the skeleton is developing during fetal development, and in childhood.

When a bone develops from a fibrous membrane, the process is called **intramembranous ossification**. Intramembranous ossification usually happens in flat bones such as the cranial bones and the clavicles. During intramembranous ossification in the developing fetus, the future bones are first formed as connective tissue membranes. Osteoblasts migrate to the membranes and secrete osteoid, which becomes mineralized and forms bony matrix. When the osteoblasts are surrounded by matrix they are called osteocytes. Eventually, a bone collar of compact bone develops and marrow develops inside the bone.

Bone Elongation

An infant is born with zones of cartilage, called epiphyseal plates, shown in **Figure** 21.10, between segments of bone to allow further growth of the bone. When the child reaches skeletal maturity (between the ages of 18 and 25 years), all of the cartilage in the plate is replaced by bone, which stops further growth.

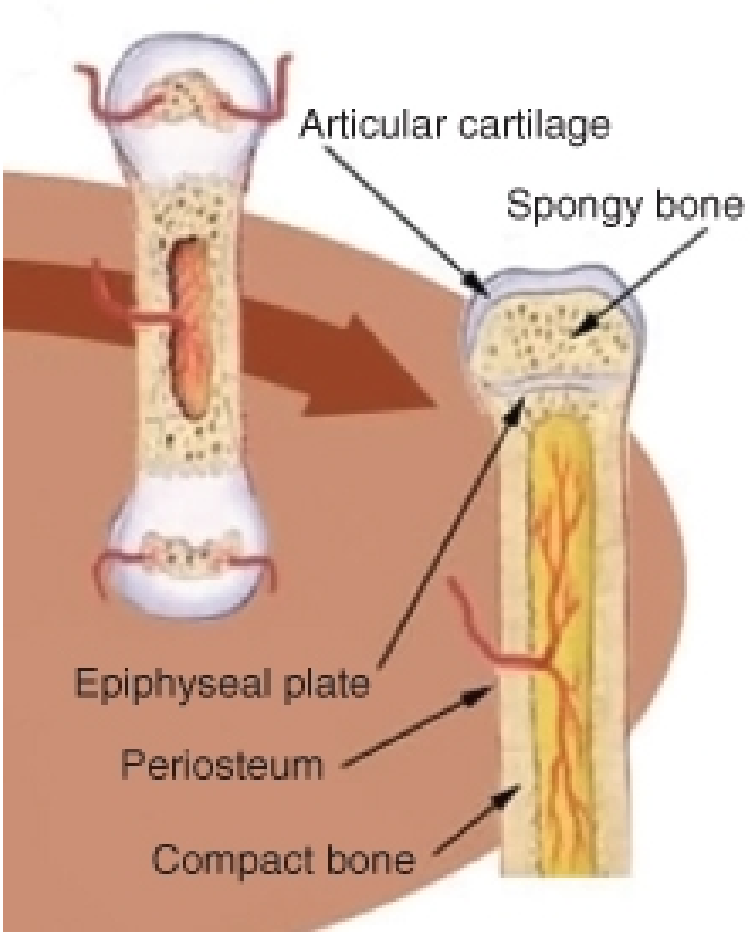

Figure 21.10: Location of the epiphyseal plate in an immature long bone. The chondrocytes in the epiphyseal plate are very metabolically active, as they constantly reproduce by mitosis. As the older chondrocytes move away from the plate they are replaced by osteoblasts that mineralize this new area, and the bone lengthens.

Bones grow in length at the epiphyseal plate by a process that is similar to endochondral ossification. The chondrocytes (cartilage cells) in the region of the epiphyseal plate grow by mitosis and push older chondrocytes down toward the bone shaft (diaphysis). Eventually these chondrocytes age and die. Osteoblasts move into this region and replace the chondrocytes with bone matrix. This process lengthens the bone and continues throughout childhood and the adolescent years until the cartilage growth slows down and finally stops. When cartilage growth stops, usually in the early twenties, the epiphyseal plate completely ossifies so that only a thin epiphyseal line remains and the bones can no longer grow in length. Bone growth is under the influence of growth hormone from the anterior pituitary gland and sex hormones from the ovaries and testes.

Even though bones stop growing in length in early adulthood, they can continue to increase in thickness or diameter throughout life in response to stress from increased muscle activity or to weight-bearing exercise.

Joints

A **joint** (also called an articulation), is a point at which two or more bones make contact. They are constructed to allow movement and provide mechanical support for the body. Joints are a type of lever, which is a rigid object that is used to increase the mechanical force that can be applied to another object. This reduces the amount of energy that need to be spent in moving the body around. The articular surfaces of bones, which are the surfaces that meet at joints, are covered with a smooth layer of articular cartilage.

There are three types of joints: immovable, partly movable, and synovial. See http://www.youtube.com/watch?v=SOMFX_83sqk&feature=related for a brief overview of the types of joints.

- **Immovable Joint**: At an immovable joint (or a fixed joint), bones are connected by dense connective tissue, which is usually collagen. Immovable joints, like those connecting the cranial bones, have edges that tightly interlock, and do not allow movement. The connective tissue at immovable joints serves to absorb shock that might otherwise break the bone.

- **Partly Movable Joints**: At partly movable joints (or cartilaginous joints), bones are connected entirely by cartilage. Cartilaginous joints allow more movement between bones than a fibrous joint does, but much less than the highly mobile synovial joint. Examples of partly-movable joint include the ribs, the sternum and the vertebrae, shown in **Figure** 21.11. Partly-movable joints also form the growth regions of immature long bones.

- **Synovial joints**: Synovial joints, also known as movable joints, are the most mobile joints of all. They are also the most common type of joint in the body. Synovial joints

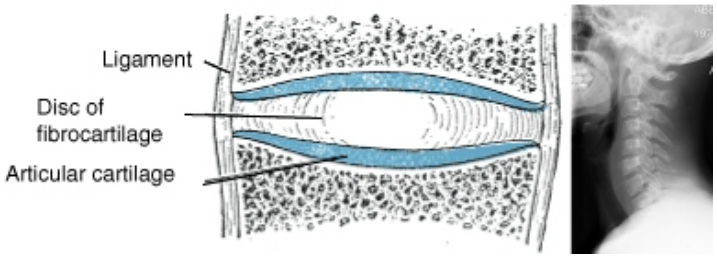

Figure 21.11: Illustration of an synovial disk, a cartilaginous joint. These partly-movable joints are found between the vertebrae. An X ray of the cervical (neck) vertebrae is at right.

contain a space between the bones of the joint (the articulating bones), which is filled with synovial fluid. **Synovial fluid** is a thick, stringy fluid that has the consistency of egg albumin. The word "synovial" comes from the Latin word for "egg". The fluid reduces friction between the articular cartilage and other tissues in joints and lubricates and cushions them during movement. There are many different types of synovial joints, and many different examples. A synovial joint is shown in **Figure** 21.12.

The outer surface of the synovial joint contains ligaments that strengthen joints and holds bones in position. The inner surface (the synovial membrane) has cells producing synovial fluid that lubricates the joint and prevents the two cartilage caps on the bones from rubbing together. Some joints also have tendons which are bands of connective tissue that link muscles to bones. Bursae are small sacs filled with synovial fluid that reduce friction in the joint. The knee joint contains 13 bursae. Synovial joints can be classified by the degree of mobility they allow, as shown in **Figure** 21.13.

In a ball and socket joint the ball-shaped surface of one bone fits into the cuplike depression of another. The ball-and-socket joint consists of one bone that is rounded and that fits within a cuplike bone. Examples of a ball and socket joint include the hip (**Figure** 21.15) and shoulder.

In an ellipsoidal joint an ovoid articular surface, fits into an elliptical cavity in such a way as to permit of some back and forth movement, but not side-to-side motion. The wrist-joint and knee (**Figure** 21.14), are examples of this type of joint.

In a saddle joint the opposing bone surfaces are fit together like a person sitting in a saddle. The movements at a saddle joint are the same as in an ellipsoid joint. The best example of this form is the joint between the carpals and metacarpals of the thumb.

In the hinge joint, the articular surfaces fit together in such a way as to permit motion only in one plane, forward and backward, the extent of motion at the same time being considerable. An example of a hinge joint is the elbow.

The pivot joint is formed by a process that rotates within a ring, the ring being formed partly of bone, and partly of ligament. An example of a pivot joint is the joint between the

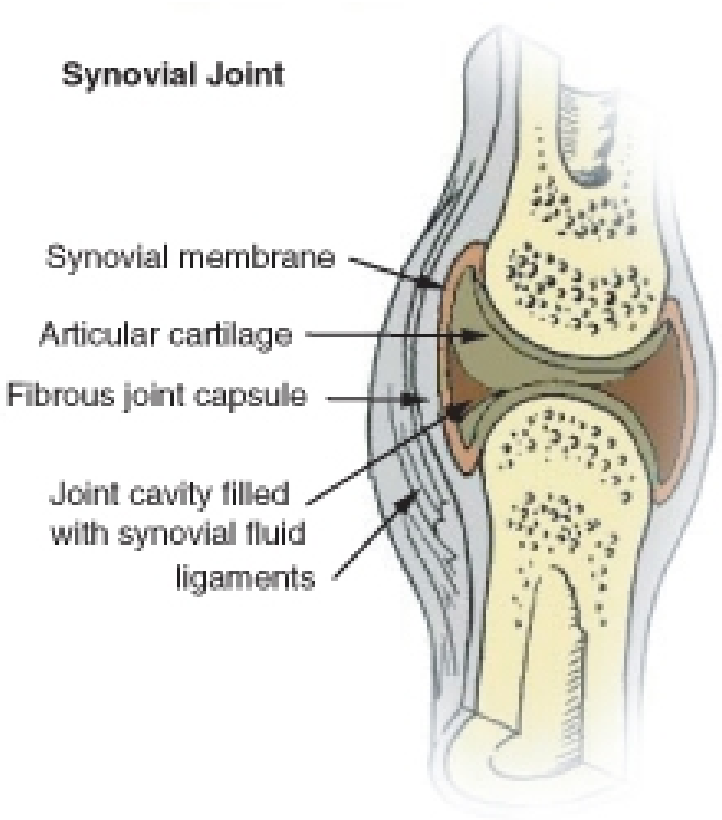

Figure 21.12: Diagram of a synovial joint. Sinovial joints are the most common type of joint in the body, and allow a wide range of motions. Think of how difficult walking would be if your knees and hips were only partly movable, like your spine.

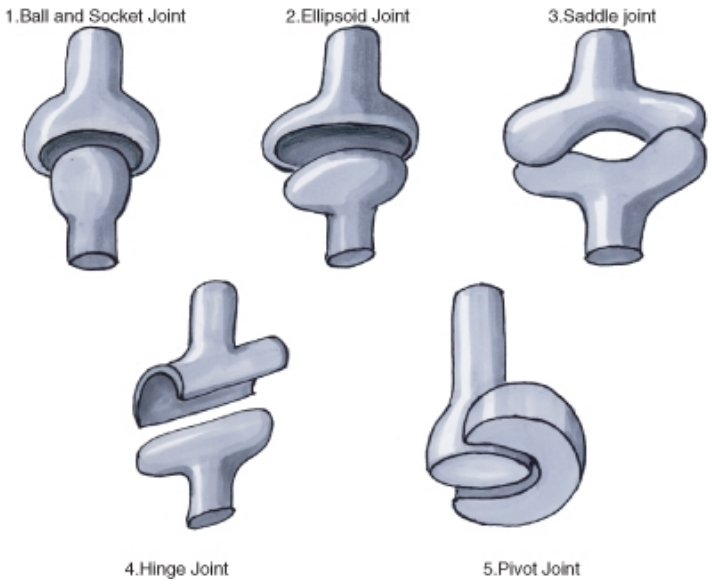

Figure 21.13: Types of Synovial joints. These fully-movable joints between bones allow a wide range of motions by the body. They also help reduce the amount of energy that needs to move the body.

radius and ulna that allows you to turn the palm of your hand up and down.

A gliding joint, also known as a plane joint, is a joint which allows one bone to slide over another, such as between the carpels of the fingers. Gliding joints are also found in your wrists and ankles.

Not all bones are interconnected directly: There are 6 bones in the middle ear called the ossicles (three on each side) that articulate only with each other. The hyoid bone which is located in the neck and serves as the point of attachment for the tongue, does not articulate with any other bones in the body, being supported by muscles and ligaments. The longest and heaviest bone in the body is the femur and the smallest is the stapes bone in the middle ear. In an adult, the skeleton makes up around 20% of the total body weight.

Homeostatic Imbalances of Bone

Despite their great strength, bones can **fracture**, or break. Fractures can occur at different places on a bone, and are usually due to excessive bending stress on the bone. Fractures can be complete in which the bone is completely broken, or incomplete in which the bone is cracked or chipped, but not broken all the way, as shown in **Figure** 21.16. Immediately after a fracture, blood vessels that were torn leak blood into surrounding tissues and a mass of clotted blood, called a hematoma, forms. The area becomes swollen and sore. Within a few days capillaries begin to grow into the hematoma and white blood cells clean up the dead and dying cells. Fibroblasts and osteoblasts arrive and begin to rebuild the bone. Fibroblasts

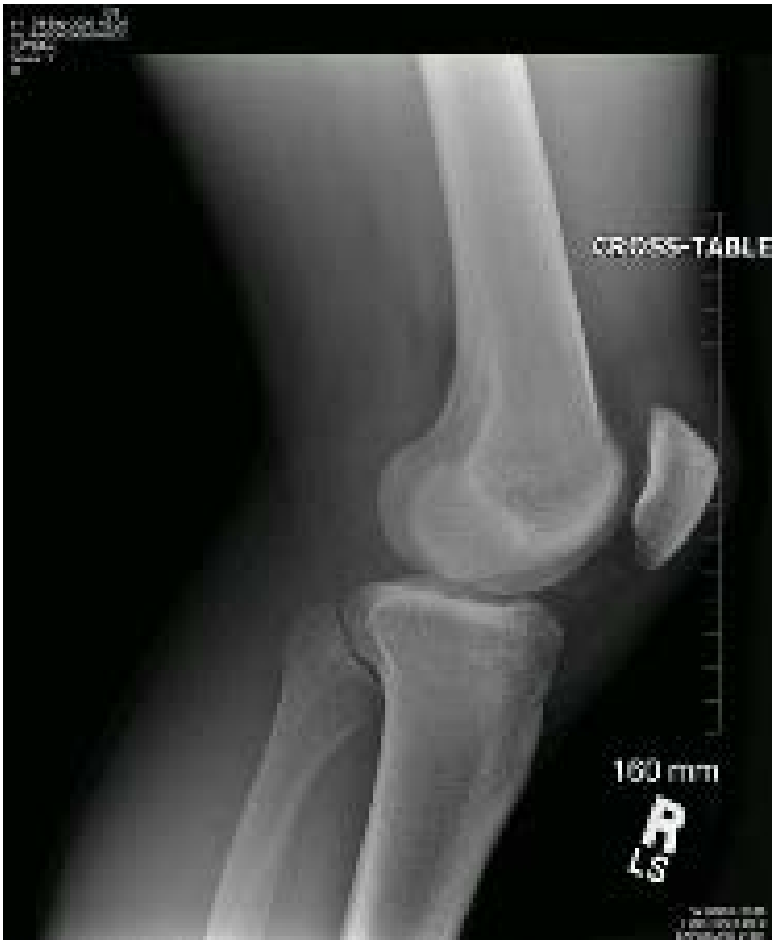

Figure 21.14: Knee joint, an ellipsoid joint.

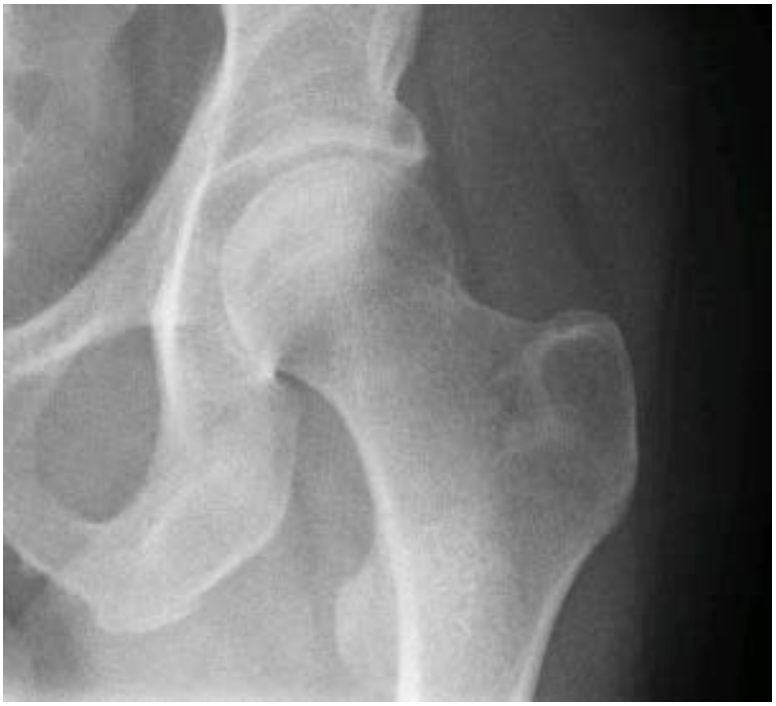

Figure 21.15: The hip joint is a ball-and-socket joint.

produce collagen fibers which span the area of the break and connect the ends of the broken bone together. Osteoblasts begin to form spongy bone, and chondroblasts form cartilage matrix. Later, the cartilage and spongy bone are replaced by a bony growth called a callus which forms about 3 to 4 weeks after the fracture, and continues until the break is firmly sealed 2 to 3 months later. Eventually the bony callus is replaced by spongy and compact bone, similar to the rest of the bone.

Rickets is a softening of the bones in children which potentially leads to fractures and deformity; bowing of the leg bones is shown in **Figure** 21.17. Rickets is among the most frequent childhood diseases in many developing countries. The most common cause is a vitamin D deficiency. Vitamin D is needed by the body to absorb calcium from foods and to form bones. However, lack of calcium in the diet may also cause rickets. Although it can occur in adults, most cases of rickets occur in children who suffer from severe malnutrition, which usually results from starvation during early childhood. Osteomalacia is the term used to describe a similar condition occurring in adults, generally due to a deficiency of vitamin D. Osteomalacia can result in bone pain, difficulty in putting weight on bones, and sometimes fractures.

Some studies show most people get enough Vitamin D through their food and exposure to ultraviolet (UV) radiation in sunlight. Vitamin D is produced by certain skin cells from a compound found inside the cells. The skin cells need UV light for this reaction to happen. However, eating foods to which vitamin D has been added or taking a dietary supplement pill

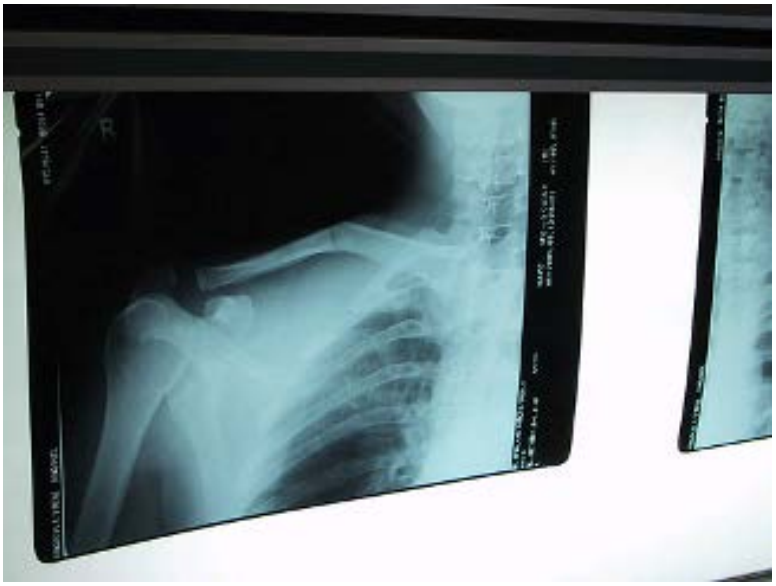

Figure 21.16

is usually preferred to UV exposure, due to the increased risk of sun burn and skin cancer. Many countries have fortified certain foods such as milk, bread, and breakfast cereals with Vitamin D to help prevent deficiency.

Osteoporosis is a disease in which the breakdown of bone matrix by osteoclasts is greater than the building of bone matrix by osteoblasts. This results in bone mass that is greatly decreased, causing bones to become lighter and more porous. Bones are then more prone to breakage, especially the vertebrae and femurs. Compression fractures of the vertebrae and hip breaks, in which the top (or head) of the femur breaks are common, and can lead to further immobility, making the disease worse. Osteoporosis mostly occurs in older women and is linked to the decrease in production of sex hormones. However, poor nutrition, especially diets that are low in calcium and vitamin D, increase the risk of osteoporosis in later life. One of the easiest ways to prevent osteoporosis is to eat a healthful diet that has adequate calcium and vitamin D. For a brief animation of osteoporosis, see http://www.youtube.com/watch?v=5uAXX5GvGrI.

Osteoarthritis is a condition in which wearing and breakdown of the cartilage that covers the ends of the bones leads to pain and stiffness in the joint. Decreased movement of the joint because of the pain may lead to muscles that are attached to the joint to become weaker, and ligaments may become looser. Osteoarthritis is the most common form of arthritis. Some of the most common causes include old age, sport injuries to the joint, bone fractures, and overweight and obesity. Total hip replacement is a common treatment for osteoarthritis. An X ray image of a replacement hip joint is shown in **Figure** 21.18. For a brief animation of osteoarthritis, see http://www.youtube.com/watch?v=0dUSmaev5b0.

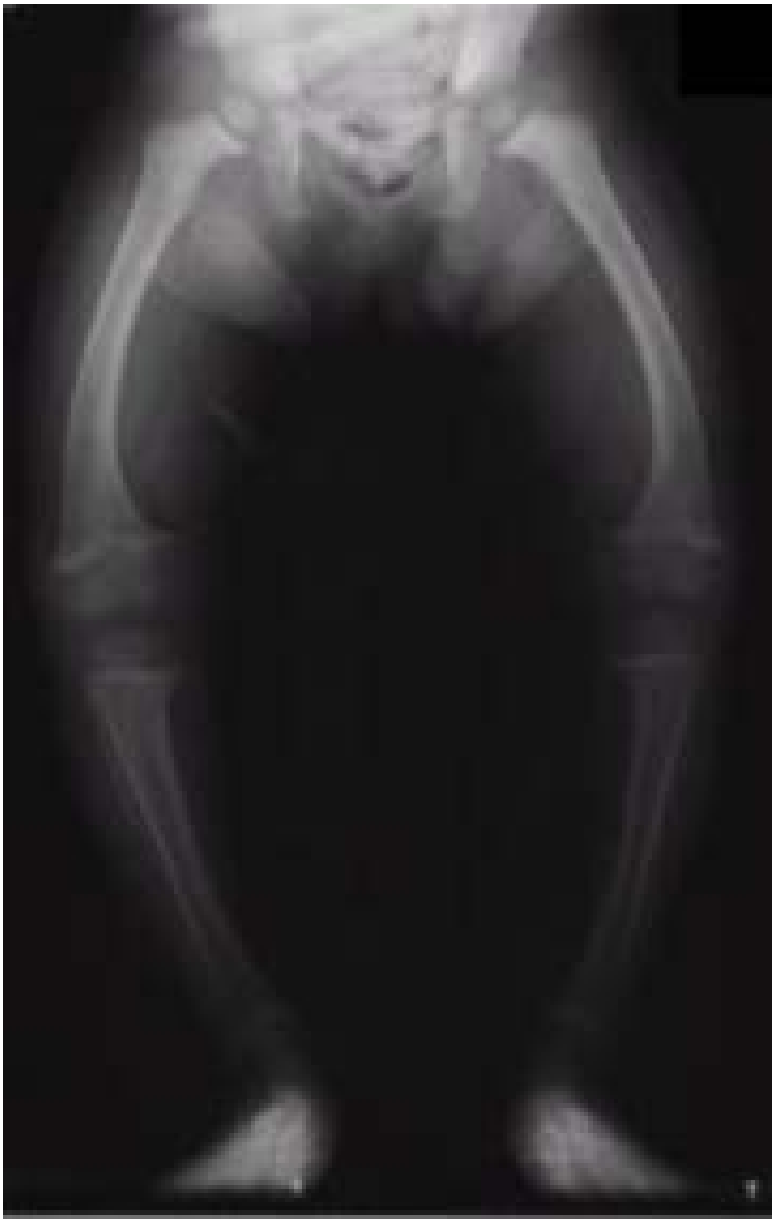

Figure 21.17: An X ray image of a 2-year-old who shows the typical bowing of the femurs that occurs in rickets. Rickets causes poor bone mineralization, which results in the bones bending under the weight of the body.

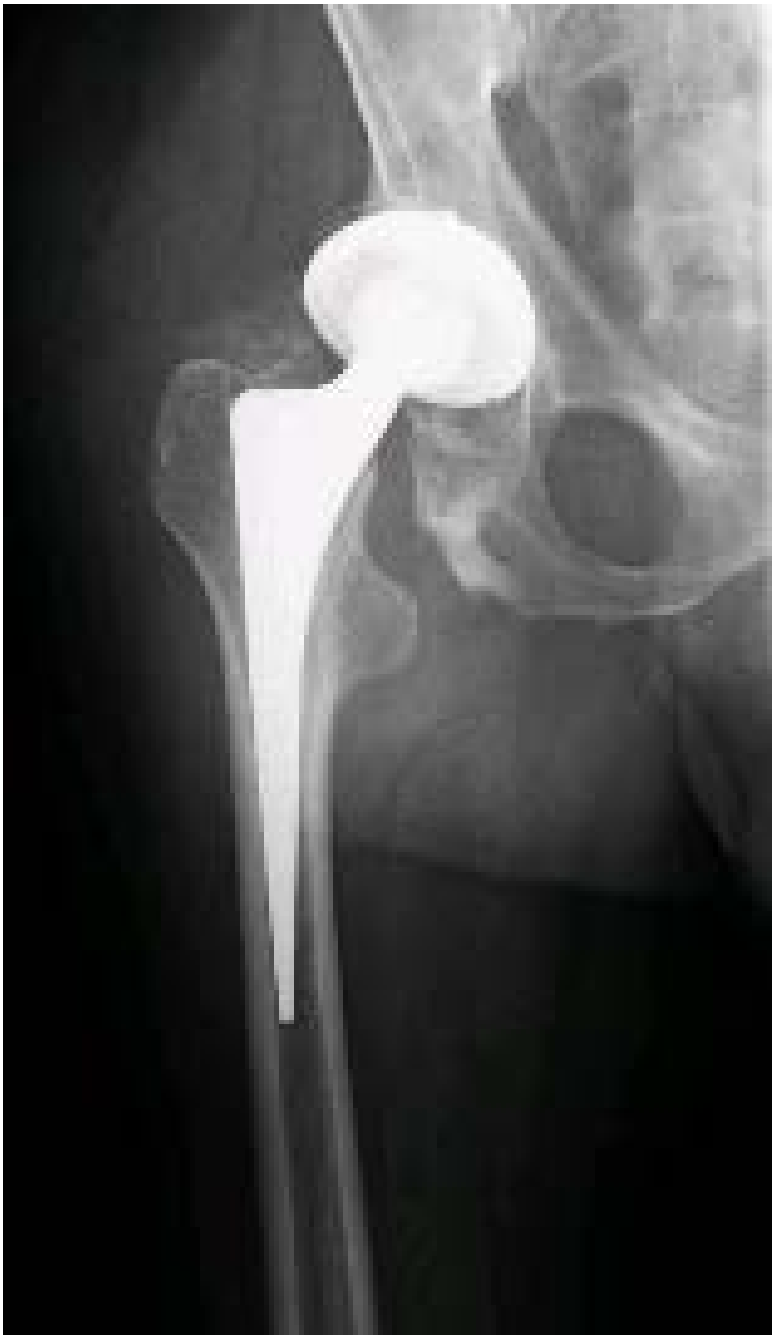

Figure 21.18: Total replacement of hip joint. One of the leading reasons for hip replacement is osteoarthritis of the joint in which the cartilage around the top of the femur bone deteriorates over time, and causes the bones of the joint to grind painfully against each other. This can result in a narrowing of the space in the ball-and-socket joint structure, causing limited movement of the hip and constant pain in the hip joint.

Lesson Summary

- The human skeleton is well adapted for the functions it must perform. Functions of bones include support, protection, movement, mineral storage, and formation of blood cells.
- The adult human skeleton usually consists of 206 named bones and these bones can be grouped in two divisions: axial skeleton and appendicular skeleton.
- There are two types of bone tissue: compact and spongy. Compact bone consists of closely packed osteons, or Haversian systems. Spongy bone consists of plates of bone, called trabeculae, around irregular spaces that contain red bone marrow.
- Osteogenesis is the process of bone formation. Three types of cells, osteoblasts, osteocytes, and osteoclasts, are involved in bone formation and remodeling.
- In intramembranous ossification, connective tissue membranes are replaced by bone. This process occurs in the flat bones of the skull. In endochondral ossification, bone tissue replaces hyaline cartilage models. Most bones are formed in this manner.
- Bones grow in length at the epiphyseal plate between the diaphysis and the epiphysis. When the epiphyseal plate completely ossifies, bones no longer increase in length.
- Bones may be classified as long, short, flat, or irregular. The diaphysis of a long bone is the central shaft. There is an epiphysis at each end of the diaphysis.
- There are three types of joints in terms of the amount of movement they allow: immovable, partly movable, and synovial joints (which are freely movable).

Review Questions

1. Identify an example of a cell, a tissue, and an organ of the skeletal system.
2. Identify the main bones of the axial skeleton.
3. Identify the main bones of the appendicular skeleton.
4. List four functions of bones and the skeleton.
5. What is endochondrial ossification, and when does it occur?
6. Name the three main types of joints, and identify a location in the body that is an example of that type of joint.
7. Outline how a bone fracture is repaired.
8. What is the purpose of Haversian canals?
9. Leukemia is a type of cancer that affects bone. It is a disease in which there is an overproduction of immature white blood cells. Identify the area of bone that is affected by leukemia.

Further Reading / Supplemental Links

- Anatomy and Physiology © 2002 Elaine Marieb. Published by Pearson Education Inc. as Benjamin Cummings.

- Biology 6th Edn. © 2002 Campbell and Reece. Published by Pearson Education Inc. as Benjamin Cummings.
- http://training.seer.cancer.gov/module_anatomy/unit3_5_skeleton_divisions
- http://training.seer.cancer.gov/module_anatomy/unit3_1_bone_functions
- http://yucky.discovery.com/noflash/body/pg000124
- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookMUSSKEL
- http://en.wikipedia.org

Vocabulary

appendicular skeleton The portion of the human skeleton that includes the bones of the limbs, scapula and the pelvis.

axial skeleton The portion of the human skeleton that includes the bones of the head, vertebral column, ribs and sternum.

bone marrow A soft, connective tissue found in the interior bones. Red bone marrow produces red blood cells and white blood cells are produced by yellow bone marrow.

bone matrix A mixture of calcium salts, such as calcium phosphate and calcium hydroxide, and collagen fibers (a type of protein), which form hollow tubes that look similar to the rings on a tree.

cartilage Dense connective tissue that is made of tough protein fibers. The function of cartilage in the adult skeleton is to provide smooth surfaces for the movement of bones at a joint.

compact bone A type of tissue that makes up the dense outer layer of bones.

endochondrial ossification The process of replacing cartilage with bony tissue, occurs during the gestation period and for years after birth.

endoskeleton The sturdy internal framework of bones and cartilage that is found inside vertebrates.

epiphyseal plate Also known as the growth plate, the area of cartilage at the end of long bones, responsible for elongation of the bone.

fracture A break in a bone.

haversian canal Located in the center of each osteon, serves as a passageway for blood vessels and nerves.

intramembranous ossification The process of bone tissue developing from a fibrous membrane, usually occurs in flat bones, such as the clavicle.

joint A point at which two or more bones make contact; also called an articulation.

ligament A band of tough, fibrous tissue that connects a bone to another bone.

osteoarthritis A condition in which wearing and breakdown of the cartilage that covers the ends of the bones leads to pain and stiffness in the joint.

osteoblast A type of bone cell that secretes the organic content of bone matrix, and is responsible for the growth of new bone.

osteoclast A type of bone cell that removes calcium salts from bone matrix.

osteocyte A type of bone cell that is responsible for monitoring the protein and mineral content of the bone, directing the release of calcium into the blood, and directing the uptake up of calcium salts into the bone.

osteons Cylinder-shaped units that act like strong pillars within compact bone to give strength, allow the bone to bear the weight of the attached muscles, and withstand the stresses of movement.

osteoporosis A disease in which the breakdown of bone matrix by osteoclasts is greater than the building of bone matrix by osteoblasts.

periosteum The tough, shiny, white membrane that covers all surfaces of bones except at the joint surfaces.

rickets A common disease among children in developing countries; symptoms include soft bones that are prone to fractures.

spongy bone A type of tissue that is less dense than compact bone, and is found toward the center of the bone.

synovial fluid A thick fluid that reduces friction between the articular cartilage and other tissues in synovial (moveable) joints and lubricates and cushions them during movement.

Points to Consider

- Consider how what you eat today can influence your chance of developing osteoporosis later in life.
- Forensic pathologists can estimate the age of a deceased person even if only their skeleton remains. Consider how this is possible.

21.2 Lesson 21.2: Muscular System

Lesson Objectives

- Outline the major role of the muscular system.
- Relate muscle fibers, fascicles, and muscles to the muscular system.
- Explain how muscle fibers contract.
- Examine the role of ATP and calcium in muscle contraction.
- Outline how muscles move bones.
- Explain how muscles respond to aerobic and anaerobic exercise.

Introduction

The muscular system is the biological system of humans that allows them to move. The muscular system, in vertebrates, is controlled through the nervous system. Much of your muscle movement occurs without your conscious control and is necessary for your survival. The contraction of your heart and peristalsis, the intestinal movements that pushes food through your digestive system, are examples of involuntary muscle movements. Involuntary muscle movement is controlled by the autonomic nervous system. Voluntary muscle contraction is used to move the body and can be finely controlled, such as the pincer-type movement of the fingers that is needed to pick up chess pieces, or the gross movements of legs arm, and the torso that are needed in skating, shown in **Figure** 21.19. Voluntary muscle movement is controlled by the somatic nervous system.

Muscle Tissues

Each muscle in the body is composed of specialized structures called muscle fibers. **Muscle fibers** are long, thin cells that have a special talent that other cells do not have—they are able to contract. Muscles, where attached to bones or internal organs and blood vessels, are responsible for movement. Nearly all movement in the body is the result of muscle contraction. Exceptions to this are the action of cilia, the flagellum on sperm cells, and the amoeboid movement of some white blood cells.

Three types of muscle tissue are in the body: skeletal, smooth, and cardiac.

Figure 21.19: You need muscles to play chess. Playing chess requires fine motor movement, but not a lot of gross muscle movements. Skating on the other hand, requires a lot of gross muscle movement of the limbs and the entire body.

- **Skeletal muscle** is usually attached to the skeleton. Skeletal muscles are used to move the body. They generally contract voluntarily (controlled by the somatic nervous system), although they can also contract involuntarily through reflexes.
- **Smooth muscle** is found within the walls of organs and structures such as the esophagus, stomach, intestines, bronchi, uterus, urethra, bladder, and blood vessels. Unlike skeletal muscle, smooth muscle is involuntary muscle which means it not under your conscious control.
- **Cardiac muscle** is also an involuntary muscle but is a specialized kind of muscle found only within the heart.

Cardiac and skeletal muscles are striated, in that they contain highly-regular arrangements of bundles of protein fibers that give them a "striped" appearance. Smooth muscle does not have such bundles of fibers, and is non-striated. While skeletal muscles are arranged in regular, parallel bundles, cardiac muscle fibers connect at branching, irregular angles. Skeletal muscle contracts and relaxes in short, intense bursts, whereas cardiac muscle contracts constantly for 70 to 80 years (an average life span), or even longer.

Skeletal Muscle

Skeletal muscle, which is attached to bone, is responsible for body movements and body posture. There are approximately 639 skeletal muscles in the human body, some of which are shown in **Figure** 21.20. These muscles are under conscious, or voluntary, control. The basic units of skeletal muscle are muscle cells that have many nuclei. These muscle cells also contain light and dark stripes called striations, which are shown in **Figure** 21.21. The striations are a result of the orientation of the contractile proteins inside the cells. Skeletal muscle is therefore called striated muscle. Each muscle cell acts independently of its neighboring muscle cells. On average, adult males are made up of 40 to 50 percent skeletal muscle tissue and an adult female is made up of 30 to 40 percent skeletal muscle tissue.

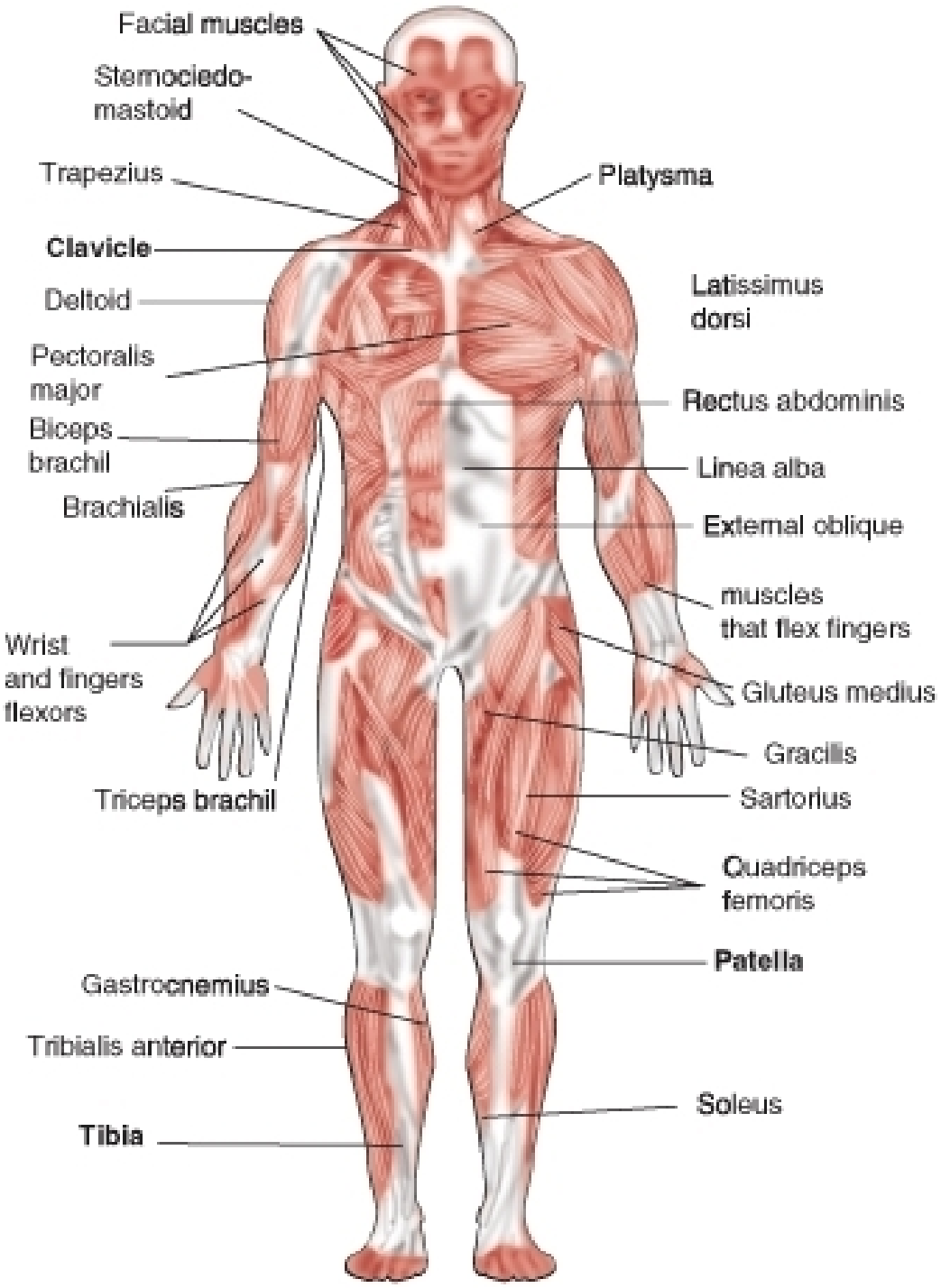

Figure 21.20: Frontal view of the major skeletal muscles. You would not see smooth and cardiac muscles included in diagrams of the muscular system because such diagrams usually show only the muscles that move the body (skeletal muscles).

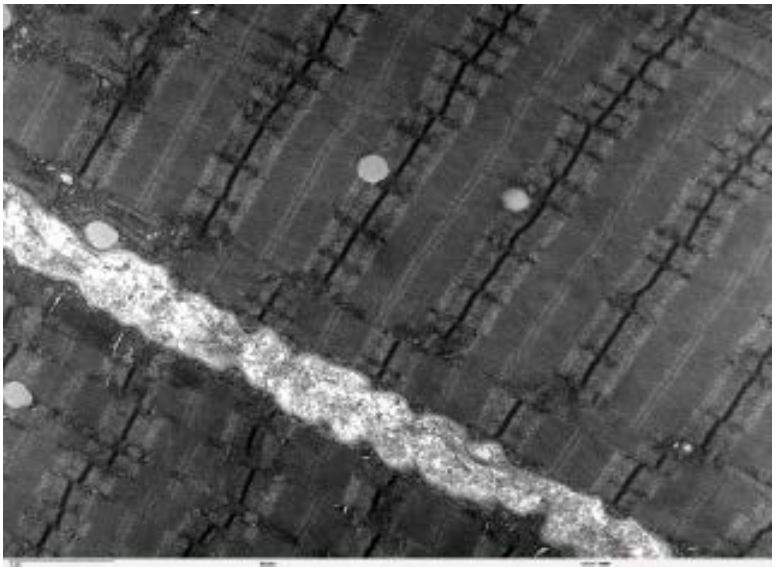

Figure 21.21: Micrograph of skeletal muscle. The stripy appearance of skeletal muscle tissue is due to long protein filaments that run the length of the fibers.

Smooth Muscle

Smooth muscle is found in the walls of the hollow internal organs such as blood vessels, the intestinal tract, urinary bladder, and uterus. It is under control of the autonomic nervous system. This means that smooth muscle cannot be controlled consciously, so it is also called involuntarily muscle. Smooth muscle cells do not have striations, and so smooth muscle is also called non-striated muscle. Smooth muscle cells are spindle-shaped and have one central nucleus. The cells are generally arranged in sheets or bundles, rather than the regular grouping that skeletal muscle cells form, and they are connected by gap junctions. Gap junctions are little pores or gaps in the cell membrane that link adjoining cells and they allowing quick passage of chemical messages between cells. Smooth muscle is very different from skeletal muscle and cardiac muscle in terms of structure and function, as shown in **Figure** 21.22. Smooth muscle contracts slowly and rhythmically.

Cardiac Muscle

Cardiac muscle, which is found in the walls of the heart, is under control of the autonomic nervous system, and so it is an involuntary muscle. A cardiac muscle cell has characteristics of both a smooth muscle and skeletal muscle cell. It has one central nucleus, similar to smooth muscle, but it striated, similar to skeletal muscle. The cardiac muscle cell is rectangular in shape, as can been seen in **Figure** 21.23. The contraction of cardiac muscle is involuntary, strong, and rhythmical. Cardiac muscle has many adaptations that makes it highly resistant to fatigue. For example, it has the largest number of mitochondria per cell of any muscle type.

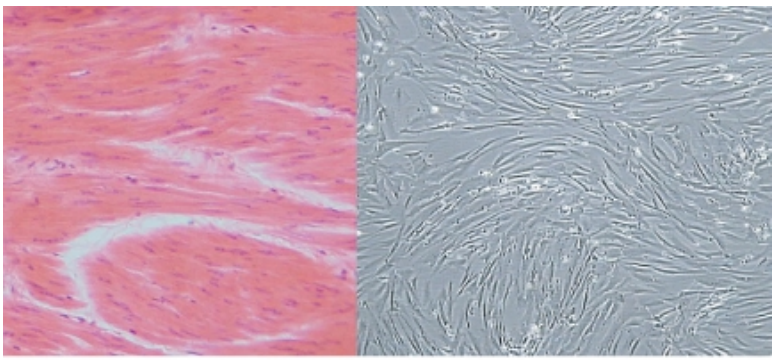

Figure 21.22: Smooth muscle. The appearance of smooth muscle is very different from skeletal and cardiac muscle. The muscle protein fibers within smooth muscle are arranged very differently to the protein fibers of skeletal or cardiac fibers, shown in (a). The spindly shape of smooth muscle cells can be seen in (b).

The mitochondria supply the cardiac cells with energy for constant movement. Cardiac cells also contain myoglobins (oxygen-storing pigments), and are provided with a large amount of nutrients and oxygen by a rich blood supply.

Cardiac muscle is similar to skeletal muscle in chemical composition and action. However, the structure of cardiac muscle is different in that the muscle fibers are typically branched like a tree branch, and connect to other cardiac muscle fibers through intercalcated discs, which are a type of gap junction. A close-up of an intercalated disc is shown in **Figure** 21.23. Cardiac muscle fibers have only one nucleus.

Structure of Muscle Tissue

A whole skeletal muscle is an organ of the muscular system. Each skeletal muscle consists of skeletal muscle tissue, connective tissue, nerve tissue, and vascular tissue. Skeletal muscles vary considerably in size, shape, and arrangement of fibers. They range from extremely tiny strands such as the tiny muscles of the middle ear to large masses such as the quadriceps muscles of the thigh.

Each skeletal muscle fiber is a single large, cylindrical muscle cell. Skeletal muscle fibers differ from "regular" body cells. They are multinucleated, which means they have many nuclei in a single cell; during development many stem cells called myoblasts fuse together to form muscle fibers. Each nucleus in a fiber originated from a single myoblast. Smooth and cardiac muscle fibers do not develop in this way.

An individual skeletal muscle may be made up of hundreds, or even thousands, of muscle fibers that are bundled together and wrapped in a connective tissue covering called epimysium. Fascia, connective tissue outside the epimysium, surrounds and separates the skeletal

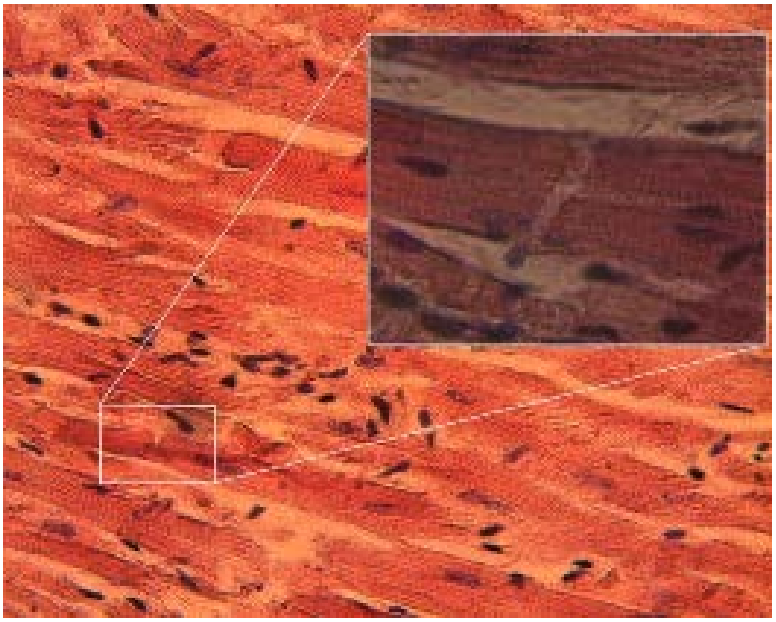

Figure 21.23: Cardiac muscle. Cardiac muscle fibers are connected together through intercalated discs.

muscles. Portions of the epimysium fold inward to divide the muscle into compartments called fascicles. Each fascicle compartment contains a bundle of muscle fibers, as shown in **Figure** 21.24.

Skeletal muscle fibers, like body cells, are soft and fragile. The connective tissue covering give support and protection for the delicate cells and allow them to withstand the forces of contraction. The coverings also provide pathways for the passage of blood vessels and nerves. Active skeletal muscle needs efficient delivery of nutrients and oxygen, and removal of waste products, both of which are carried out by a rich supply of blood vessels.

Muscles and Bones

Muscles move the body by contracting against the skeleton. Muscles can only actively contract, they extend (or relax) passively. The ability of muscles to move parts of the body in opposite directions requires that they be attached to bones in pairs which work against each other (called antagonistic pairs). Generally, muscles are attached to one end of a bone, span a joint, and are attached to a point on the other bone of the joint. Commonly, the connective tissue that covers the muscle extends beyond the muscle to form a thick ropelike structure called a tendon, as shown in **Figure** 21.24. One attachment of the muscle, the origin, is on a bone that does not move when the muscle contracts. The other attachment point, the insertion, is on the bone that moves. Tendons and muscles work together and exert only a pulling force on joints.

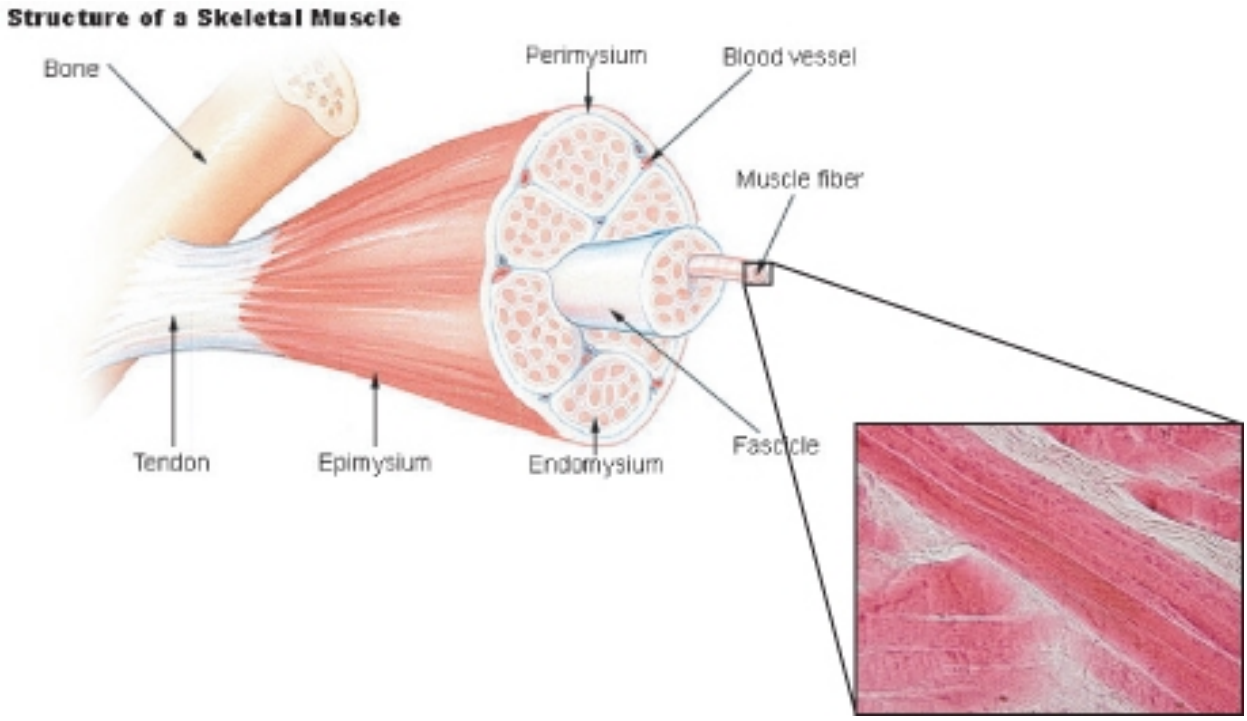

Figure 21.24: Individual bundles of muscle fibers are called fascicles. The cell membrane surrounding each muscle fiber is called the , and beneath the sarcolemma lies the sarcoplasm, which contains the cellular proteins, organelles, and myofibrils. The myofibrils are composed of two major types of protein filaments: the thinner actin filament, and the thicker myosin filament. The arrangement of these two protein filaments gives skeletal muscle its striated appearance.

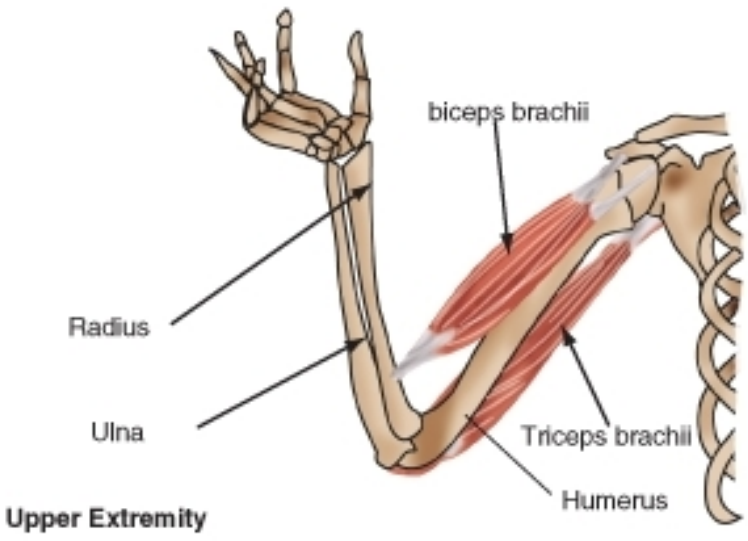

Figure 21.25: Movement of the elbow joint involves muscles and bones. The contraction of the biceps brachii muscle pulls on the radius, its point of insertion, which causes the arm to bend. To straighten the arm, the triceps brachii muscle contracts and pulls on the ulna, this causes the arm to straighten.

For example, when you contract your biceps brachii muscles, shown in **Figure** 21.25, the force from the muscles pulls on the radius bone (its point of insertion) causing the arm to move up. This action decreases the angle at the elbow joint (flexion). Flexion of the elbow joint is shown in **Figure B** 21.26. A muscle that causes the angle of a joint to become smaller is called a **flexor**. To extend, or straighten the arm, the biceps brachii relaxes and the triceps on the opposite side of the elbow joint contracts. This action is called extension, and a muscle that causes a joint to straighten out is called an **extensor**. In this way the joints of your body act like levers that reduce the amount of effort you have to expend to cause large movements of the body.

Muscle Contraction

A **muscle contraction** occurs when a muscle fiber generates tension through the movement of actin and myosin. Although you might think the term contraction means only ”shortening,” the overall length of a contracted muscle may stay the same, or increase, depending on the force working against the muscle.

Each muscle fiber contains cellular proteins and hundreds or thousands of myofibrils. Each **myofibril** is a long, cylindrical organelle that is made up of two types of protein filaments: actin and myosin. The **actin** filament is thin and threadlike, the **myosin** filament is thicker. Myosin has a “head” region that uses energy from ATP to “walk” along the actin thin

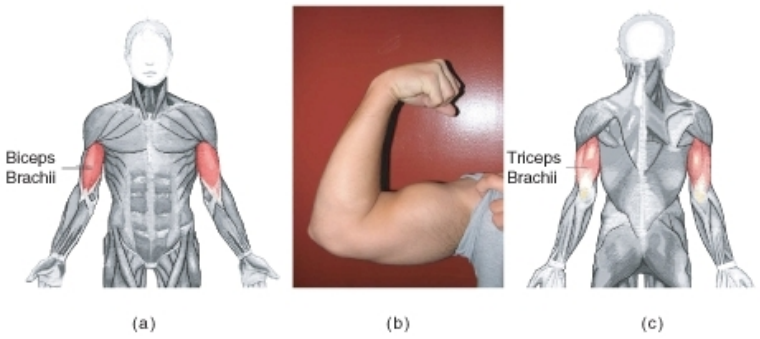

Figure 21.26: (a) The position of the biceps brachii. (b) The biceps brachii and triceps brachii act as an atagonistic pair of muscles that move the arm at the elbow joint. The biceps muscle is the flexor, and the triceps, at the back of the arm, is the extensor (c).

filament (**Figure** 21.31). The overlapping arrangement of actin and myosin filaments gives skeletal muscle its striated appearance. The actin and myosin filaments are organized into repeating units called **sarcomeres,** which can be seen in **Figure** 21.27. The thin actin filaments are anchored to structures called Z lines. The region from one Z line to the next makes up one sacromere. When each end of the myosin thick filament moves along the actin filament, the two actin filaments at opposite sides of the sacromere are drawn closer together and the sarcomere shortens, as shown in **Figure** 21.28. When a muscle fiber contracts, all sarcomeres contract at the same time, which pulls on the fiber ends.

The Neuromuscular Junction

For skeletal (voluntary) muscles, contraction occurs as a result of conscious effort that comes from the brain. The brain sends nerve signals, in the form of action potentials to the motor neuron that innervates the muscle fiber, such as the motor neuron in **Figure** 21.29. In the case of some reflexes, the signal to contract can originate in the spinal cord through a reflex arc. Involuntary muscles such as the heart or smooth muscles in the gut and vascular system contract as a result of non-conscious brain activity or stimuli endogenous to the muscle itself. Other actions such as body motion, breathing, and chewing have a reflex aspect to them; the contractions can be initiated consciously or unconsciously, but are continued through unconscious reflexes. You can learn more about action potentials and reflex arcs in the *Nervous and Endocrine Systems* chapter.

The Sliding Filament Theory

The widely accepted theory of how muscles contract is called the sliding-filament model (also known as the sliding filament theory), which is shown in **Figure** 21.30. The presence of calcium ions (Ca^{2+}) allows for the interaction of actin and myosin. In the resting state,

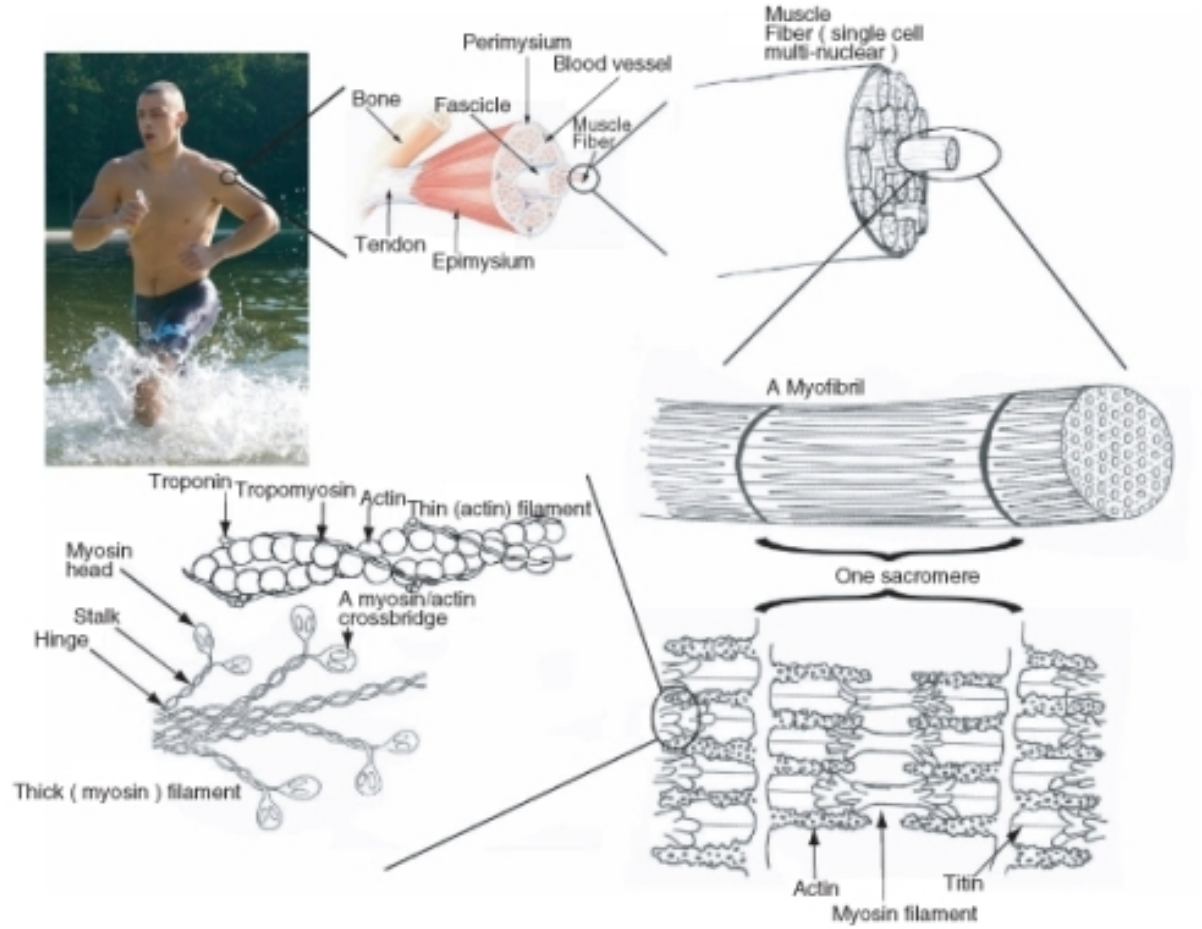

Figure 21.27: The components of muscle contraction. The sacromere is the functional unit of muscle contraction; it reaches from one Z-line to the next (also shown in). In a relaxed muscle, the actin (thin filament) and myosin (thick filament) overlap. In a muscle contraction, the filaments slide past each other, shortening the sacromere. This model of contraction is called the sliding filament mechanism.

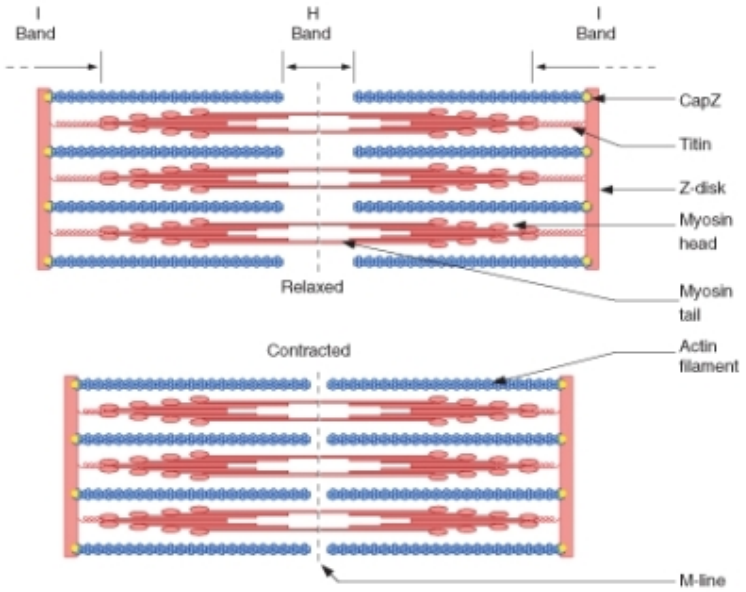

Figure 21.28: When each end of the myosin thick filament moves along the actin filament, the two actin filaments at opposite sides of the sacromere are drawn closer together and the sarcomere shortens.

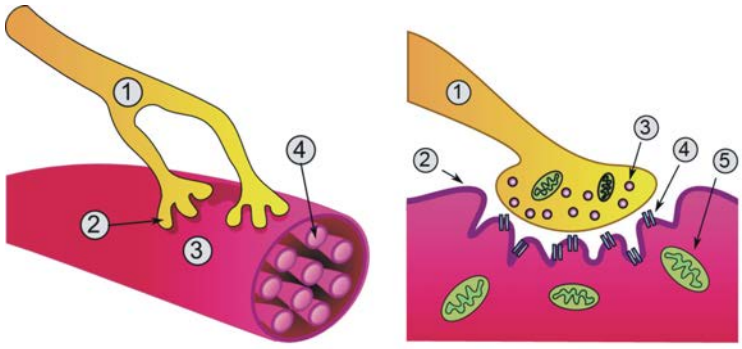

Figure 21.29: (a) A simplified diagram of the relationship between a skeletal muscle fiber and a motor neuron at a neuromuscular junction. 1. Axon; 2. Synaptical junction; 3. Muscle fiber; 4. Myofibril. (b) A close-up view of a neuromuscular junction. The neurotransmitter acetylcholine is released into the synapse and binds to receptors on the muscle cell membrane. The acetylcholine is then broken down by enzymes in the synapse. 1. presynaptic terminal; 2. sarcolemma; 3. synaptic vesicles; 4. Acetylcholine receptors; 5. mitochondrion. For an animation of the neuromuscular junction see

these proteins are prevented from coming into contact. Two other proteins, troponin and tropomyosin, act as a barrier between the actin and myosin, preventing contact between them. When Ca^{2+} binds to the actin filament, the shape of the troponin-tropomyosin complex changes, allowing actin and myosin to come into contact with each other. Below is an outline of the sliding filament theory.

1. An action potential (see the *Nervous and Endocrine Systems* chapter) arrives at the axon terminal of a motor neuron.
2. The arrival of the action potential activates voltage-dependent calcium channels at the axon terminal, and calcium rushes into the neuron.
3. Calcium causes vesicles containing the neurotransmitter acetylcholine to fuse with the plasma membrane, which releases acetylcholine into the synaptic cleft between the axon terminal and the motor end plate of the skeletal muscle fiber.
4. Activation of the acetylcholine receptors on the muscle fiber membrane opens its sodium/potassium channel, which triggers an action potential in the muscle fiber.
5. The action potential spreads through the muscle fiber's network, depolarizing the inner portion of the muscle fiber.
6. The depolarization activates specialized storage sites throughout the muscle, called the sarcoplasmic reticulum, to release calcium ions (Ca^{++}). The sarcoplasmic reticulum is a special type of smooth endoplasmic reticulum found in smooth and skeletal muscle that contains large amounts of Ca^{++}, which it stores and then releases when the cell is depolarized.
7. The calcium ions bind to actin filaments of the myofibrils and activate the actin for attachment by the myosin heads filaments.
8. Activated myosin binds strongly to the actin filament. Upon strong binding, myosin rotates at the myosin-actin interface which bends a region in the "neck" of the myosin "head," as shown in **Figure 10**.
9. Shortening of the muscle fiber occurs when the bending neck of the myosin region pulls the actin and myosin filaments across each other. Meanwhile, the myosin heads remain attached to the actin filament, as shown in **Figure** 21.30.
10. The binding of adenosine triphosphate (ATP) allows the myosin heads to detach from actin. While detached, ATP breaks down to adenosine diphosphate and an inorganic phosphate (ADP + Pi). The breaking of the chemical bond in ATP gives energy to the myosin head, allowing it to bind to actin again.
11. Steps 9 and 10 repeat as long as ATP is available and Ca^{++} is present on the actin filament. The collective bending of numerous myosin heads (all in the same direction) moves the actin filament relative to the myosin filament which causes a shortening of the sacromere. Overall, this process results in muscle contraction. The sarcoplasmic reticulum actively pumps Ca^{++} back into itself. Muscle contraction stops when Ca^{++} is removed from the immediate environment of the myofilaments.

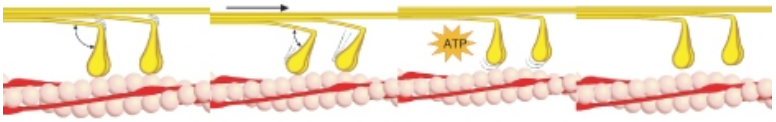

Figure 21.30: The process of actin and myosin sliding past one another is called crossbridge cycling, and it occurs in all muscle types. Myosin is a molecular motor that moves along the passive actin. Each thick myosin filament has little extensions or "heads," that "walk" along the thin actin filaments during contraction. In this way the thick filament slides over thin filament. The actin filaments transmit the force generated by myosin to the ends of the muscle, which causes the muscle to shorten.

Motor Units

It is important to remember that the sliding filament theory applies to groups of individual muscle fibers which, along with their motor neuron, are called **motor units**. A single, momentary contraction is called a muscle twitch. A twitch is the response to a single stimulus that can involve a number of motor units. As a stimulus increases, more motor units are stimulated to contract until a maximum level is reached at which point the muscle cannot exert any more force.

Each muscle fiber contracts on an "all or nothing" principle, a muscle fiber either contracts fully, or not at all, and all the fibers in a single motor unit contract at the same time. When a muscle is required to contract during exercise not all motor units are contracted at the same time. Most movements require only a small amount of the total force possible by the contraction of an entire muscle. As a result, our nervous system grades the intensity of muscle contraction by using different numbers of motor units at a time.

Cardiac Muscle Contractions

Cardiac muscle is adapted to be highly resistant to fatigue: it has a large number of mitochondria which allow continuous aerobic respiration; numerous myoglobins (oxygen storing pigment); and a good blood supply, which provides nutrients and oxygen. The heart is so tuned to aerobic metabolism that it is unable to pump well when there is a lack of blood to the heart muscle tissue, which can lead to a heart attack.

Unlike skeletal muscle, which contracts in response to nerve stimulation, and like certain types of smooth muscle, cardiac muscle is able to initiate contraction by itself. As a result, the heart can still beat properly even if its connections to the central nervous system are completely severed. A single cardiac muscle cell, if left without input, will contract rhythmically at a steady rate; if two cardiac muscle cells are in contact, whichever one contracts first will stimulate the other to contract, and so on. This inherent ability to contract is controlled by the autonomic nervous system.

If the rhythm of cardiac muscle contractions is disrupted for any reason (for example, in a heart attack or a cardiac arrest), erratic contractions called fibrillation can result. Fibrillation, which is life threatening, can be stopped by use of a device called a defibrillator. Defibrillation consists of delivering a therapeutic dose of electrical energy to the heart which depolarizes part of the heart muscle. The depolarization stops the fibrillation, and allows a normal heartbeat to start up again. Most types of defibrillators are operated by medical personnel only. However, you may be familiar with an automated external defibrillator (AED) which is shown in **Figure** 21.31.

Figure 21.31: A wall-mounted automated external defibrillator (AED). Defibrillators are used to "shock" fibrillating cardiac muscle back into the correct rhythm. AEDs are designed to be able to diagnose fibrillation in a person who has collapsed, meaning that a bystander can use them successfully with little or no training. They are usually found in areas where large groups of people may gather, such as train stations, airports, or at sports events.

Smooth Muscle Contraction

Smooth muscle-containing tissue, such as the stomach or urinary bladder often must be stretched, so elasticity is an important characteristic of smooth muscle. Smooth muscle (like cardiac muscle) does not depend on motor neurons to be stimulated. However, motor neurons of the autonomic nervous system do reach smooth muscle, causing it to contract or relax, depending on the type of neurotransmitter that is released. Smooth muscle is also affected by hormones. For example, the hormone oxytocin causes contraction of the uterus during childbirth.

Similar to the other muscle types, smooth muscle contraction is caused by the sliding of

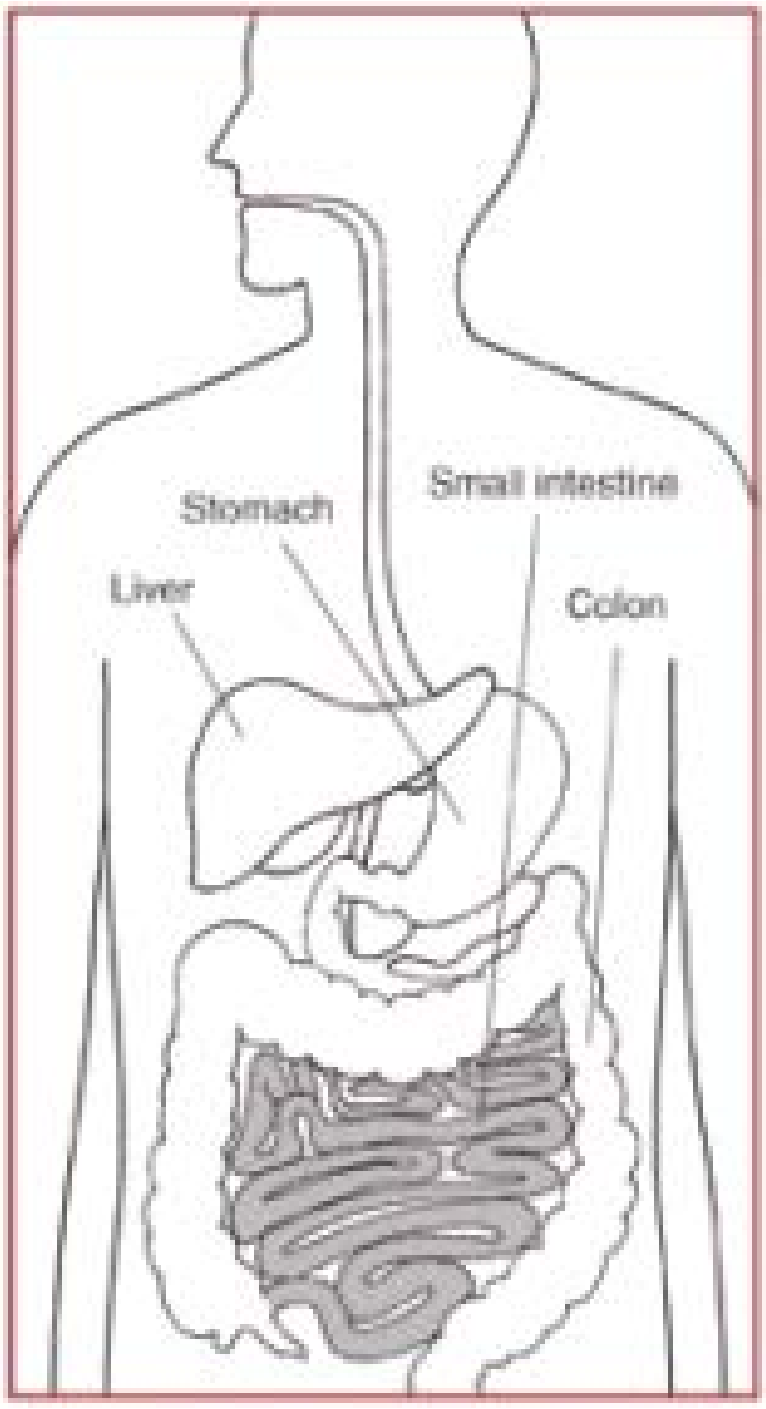

Figure 21.32: The intestinal tract contains smooth muscle which moves food along by contracting and relaxing in a process called peristalsis. An animation of peristalsis can be viewed at

myosin and actin filaments over each other. However, calcium initiates contractions in a different way in smooth muscle than in skeletal muscle. Smooth muscle may contract phasically with rapid contraction and relaxation, or tonically with slow and sustained contraction. The reproductive, digestive, respiratory, and urinary tracts, skin, eye, and vasculature all contain smooth muscle. For example, the ability of vascular smooth muscle (veins and arteries) to contract and dilate is critical to the regulation of blood pressure. Smooth muscle contracts slowly and may maintain the contraction (tonically) for prolonged periods in blood vessels, bronchioles, and some sphincters. In the digestive tract, smooth muscle contracts in a rhythmic peristaltic fashion. It rhythmically massages products through the digestive tract, shown in **Figure** 21.32, as the result of phasic contraction.

Energy Supply for Muscle Contraction

Energy for the release and movement of the myosin head along the actin filament comes from ATP. The role of ATP in muscle contraction can be observed in the action of muscles after death, at which point ATP production stops. Without ATP, myosin heads are unable to release from the actin filaments, and remain tightly bound to it (a protein complex called actomyosin). As a result, all the muscles in the body become rigid and are unable to move, a state known as rigor mortis. Eventually, enzymes stored in cells are released, and break down the actomyosin complex and the muscles become "soft" again.

Cellular respiration is the process by which cells make ATP by breaking down organic compounds from food. Muscle cells are able to produce ATP with oxygen which is called aerobic respiration, or without oxygen, an anaerobic process called anaerobic glycolysis or fermentation. The process in which ATP is made is dependent on the availability of oxygen (see *Cellular Respiration* chapter).

Aerobic ATP Production

During everyday activities and light exercise, the mitochondria of muscle fibers produce ATP in a process called aerobic respiration. **Aerobic respiration** requires the presence of oxygen to break down food energy (usually glucose and fat) to generate ATP for muscle contraction. Aerobic respiration produces large amounts of ATP, and is an efficient means of making ATP. Up to 38 ATP molecules can be made for every glucose molecule that is broken down. It is the preferred method of ATP production by body cells. Aerobic respiration requires large amount of oxygen, and can be carried out over long periods of time. As activity levels increase, breathing rate increases to supply more oxygen for increased ATP production.

Anaerobic ATP Production

When muscles are contracting very quickly, which happens during vigorous exercise, oxygen cannot travel to the muscle cells fast enough to keep up with the muscles' need for ATP. At this point, muscle fibers can switch to a breakdown process that does not require oxygen. The process, called **anaerobic gylcolysis** (sometimes called anaerobic respiration) breaks down energy stores in the absence of oxygen to produce ATP.

Anaerobic glycolysis produces only two molecules of ATP for every molecule of glucose, so it a less efficient process than aerobic metabolism. However, anaerobic glycolysis produces ATP about 2.5 times faster than aerobic respiration does. When large amounts of ATP are needed for short periods of vigorous activity, glycolysis can provide most of the ATP that is needed. Anaerobic glycolysis also uses up a large amount of glucose to make relatively small amounts of ATP. In addition to ATP, large amounts of lactic acid are also produced by glycolysis. When lactic acid builds up faster than it can be removed from the muscle, it can lead to muscle fatigue. Anaerobic glycolysis can be carried out for only about 30 to 60 seconds. Some recent studies have found evidence that mitochondria inside the muscle fibers are able to break down lactic acid (or lactate) to produce ATP, and that endurance training results in more lactate being is taken up by mitochondria to produce ATP.

Functions of Skeletal Muscle Contraction

In addition to movement, skeletal muscle contraction also fulfills three other important functions in the body: posture, joint stability, and heat production.

- Joint stability refers to the support offered by various muscles and related tissues that surround a joint.
- Heat production by muscle tissue makes them an important part of the thermoregulatory mechanism of the body. Only about 40 percent of energy input from ATP converts into muscular work, the rest of the energy is converted to thermal energy (heat). For example, you shiver when you are cold because the moving (shivering) skeletal muscles generate heat that warms you up.
- Posture, which is the arrangement of your body while sitting or standing, is maintained as a result of muscle contraction.

Types of Muscle Contractions

Skeletal muscle contractions can be categorized as isometric or isotonic.

An **isometric** contraction occurs when the muscle remains the same length despite building tension. Isometric exercises typically involve maximum contractions of a muscle by using:

- the body's own muscle (e.g., pressing the palms together in front of the body)

- structural items (e.g., pushing against a door frame)
- contracting a muscle against an opposing force such as a resistance band, or gravity, as shown in **Figure** 21.33

Figure 21.33: Pushing a heavy object involves isometric contractions of muscles in the arms and in the abdomen. This man's grip on the trolley involves isometric contractions of the hand muscles. The muscles in his legs are contracting isotonically.

An **isotonic** contraction occurs when tension in the muscle remains constant despite a change in muscle length. Lifting an object off a desk, walking, and running involve isotonic contractions. There are two types of isotonic contractions: concentric and eccentric. In a concentric contraction, the muscle shortens while generating force, such as the shortening of the biceps brachii in your arm when you lift a glass to your mouth to take a drink, or a set of dumbbells, as shown in **Figure** 21.34.

During an eccentric contraction, the force opposing the contraction of the muscle is greater than the force that is produced by the muscle. Rather than working to pull a joint in the direction of the muscle contraction, the muscle acts to slow the movement at the joint. Eccentric contractions normally occur as a braking force in opposition to a concentric contraction to protect joints from damage. The muscle lengthens while generating force. Part of training for rapid movements such as pitching during baseball involves reducing eccentric braking which allows greater power to be developed throughout the movement.

Figure 21.34: An example of an isotonic contraction. The biceps brachii contract concentrically, raising the dumbbells.

Muscles and Exercise

As we learned earlier in this lesson, your muscles are important for carrying out everyday activities, whether you are picking up a glass of orange juice, walking your dog, or snow wrestling (**Figure** 21.35). The ability of your body to carry out your daily activities without getting out of breath, sore, or overly tired is referred to as physical fitness. For example, a person who becomes breathless and tired after climbing a flight of stairs is not physically fit.

We cannot discuss the effect of exercise on your muscles without first clarifying the confusion between some common terms. It is easy to get confused with the relationship between "physical fitness," "physical activity," and "physical exercise." Some people may think they cannot fit physical activity into their lives because they are unable to afford to join a gym, they do not have the time be involved in an organized sport, or they do not want to lift weights. However, physical activity encompasses so much more than just "working out." Physical activity is any movement of the body that causes your muscles to contract and your heart rate to increase. Everyday activities such as carrying groceries, vacuuming, walking to class, or climbing a flight of stairs are physical activities.

Figure 21.35: You don't have to be super fit to play in snow, but it might help!

Being physically active for 60 minutes a day for at least five days a week helps a person to maintain a good level of physical fitness and also helps him or her to decrease their chance of developing diseases such as cardiovascular disease, Type 2 diabetes, and certain forms of cancer. Varying levels of physical activity exist: from a sedentary lifestyle in which there is very little or no physical activity, to high-level athletic training. Most people will find themselves somewhere in the middle of this wide spectrum.

Physical exercise is any activity that maintains or improves physical fitness and overall health. Exercise is often practiced to improve athletic ability or skill. Frequent and regular physical exercise is an important component in the prevention of some lifestyle diseases such as heart disease, cardiovascular disease, Type 2 diabetes and obesity. Regular exercise is also helpful with reduction in, or avoidance of symptoms of depression. Regular exercise improves both muscular strength and endurance. Muscular strength is the ability of the muscle to exert force during a contraction. Muscular endurance is the ability of the muscle to continue to contract over a period of time without getting fatigued. Regular stretching improves flexibility of the joints and helps avoid activity-related injuries.

Effect of Exercise on Muscles

Exercises are generally grouped into three types depending on the overall effect they have on the human body:

- Aerobic, or endurance, exercises, such as cycling, walking, and running, shown in **Figure** 21.36, increase muscular endurance.

- Anaerobic exercises, such as weight training, shown in **Figure** 21.37, or sprinting increase muscle strength.
- Flexibility exercises, such as stretching, improve the range of motion of muscles and joints.

Aerobic exercise causes several changes in skeletal muscle: mitochondria increase in number, the fibers make more myoglobin, and more capillaries surround the fibers. These changes result in greater resistance to fatigue and more efficient metabolism. Aerobic exercise also benefits cardiac muscle. It results in the heart being able to pump a larger volume of blood with each beat due to an increase in the size of the heart's ventricles.

Figure 21.36: Running is a form of aerobic exercise.

Anaerobic, or resistance, exercises cause an increase in muscle mass. Muscles that are trained under anaerobic conditions develop differently giving them greater performance in short duration-high intensity activities. As a result of repeated muscle contractions, muscle fibers develop a larger number of mitochondria and larger energy reserves.

During anaerobic exercise, muscles break down stored creatine phosphate to generate ATP. Creatine phosphate is an important energy store in skeletal muscle. It is broken down to form creatine for the 2 to 7 seconds following intense contractions. After several seconds, further ATP energy is made available to muscles by breaking down the storage molecule glycogen into pyruvate through glycolysis, as it normally does through the aerobic cycle. What differs is that pyruvate, rather than be broken down through the slower but more energy efficient aerobic process, is fermented to lactic acid. Muscle glycogen is restored from blood sugar, which comes from the liver, from digested carbohydrates, or from amino acids which have been turned into glucose.

Two types of muscle fibers make up skeletal muscle:

- Slow twitch muscle fibers, or "red" muscle, is dense with capillaries and is rich in mitochondria and myoglobin, giving the muscle tissue its characteristic red color. It can carry more oxygen and sustain aerobic activity. The endurance of slow twitch muscles is increased by aerobic training.
- Fast twitch muscle fibers are the fastest type of muscle fibers in humans. These fibers tend to have fewer mitochondria than slow twitch fibers do, but they have larger energy stores. They can contract more quickly and with a greater amount of force than slow-twitch fibers can. Fast twitch fibers can sustain only short, anaerobic bursts of activity before muscle contraction becomes painful. Fast twitch muscle fibers become faster and stronger in response to short, intense activities such as weight training.

Both aerobic and anaerobic exercise also work to increase the mechanical efficiency of the heart by increasing cardiac volume (aerobic exercise), or myocardial thickness (strength training). Anaerobic training results in the thickening of the heart wall to push blood through arteries that are squeezed by increased muscular contractions.

Figure 21.37: This weightlifter shows muscular hypertrophy which he has gained through anaerobic exercise.

Muscular Hypertrophy

Hypertrophy is the growth in size of muscle fibers and muscles, as shown in **Figure** 21.37. Aerobic exercise does not tend to cause hypertrophy even though the activity may go on for several hours. That is why long-distance runners tend to be slim, especially in the upper body. Hypertrophy is instead caused by high-intensity anaerobic exercises such as weight lifting or other exercises that cause the muscles to contract strongly against a resisting force. As a result of repeated muscle contractions, muscle fibers develop a larger number

of mitochondria and larger energy reserves. The muscle fibers also develop more myofibrils, and each myofibril contains more actin and myosin filaments. The effect of this activity is hypertrophy of the stimulated muscle.

Factors such as age and sex can also affect muscle hypertrophy. During puberty in males, hypertrophy occurs at an increased rate. In general, males are also able to develop larger muscles because the male body produces far more testosterone than the female body does. On average, an adult human male body produces about eight to ten times more testosterone than an adult female body. Testosterone is an anabolic steroid, which means it increases protein synthesis within muscle fibers, resulting in the buildup of more myosin and actin filaments, and myofibrils. More myofibrils means an increase in strength.

Athletic heart syndrome is hypertrophy of cardiac muscle in response to exercise. A larger heart is able to pump more blood with a single beat, resulting in a lower resting pulse rate than average. The average resting heart rate for a healthy adult is between 60 and 100 beats per minute, but an athlete can have a resting pulse rate of 40 beats per minute or less! These changes would indicate heart-disease if observed in a person who is not active, but in an athlete a large heart with a slow resting pulse is the result of normal and healthy muscle growth, and indicates a high level of fitness.

Proper rest and recovery are also as important to health as exercise, otherwise the body is in a permanently injured state and will not improve or adapt well to the exercise. Therefore, it is important to remember to allow adequate recovery time of muscles between exercise sessions. This type of rest is called active rest.

Muscle Atrophy

To remain healthy, muscles must be used. The condition in which muscle mass is lost is called **atrophy**. Atrophy can occur if muscles do not get enough exercise, or if an injury such as bone fracture causes immobility. Atrophy is the reverse of hypertrophy, muscle fibers become smaller, which causes the muscle to become smaller. Atrophy can also result from a spinal injury (CNS damage) leading to muscle paralysis, which the athlete in **Figure** 21.38 experiences. Diseases such as muscular dystrophy, amyotrophic lateral sclerosis (ALS, or Lou Gehrig's disease), and polio also cause muscle atrophy.

Homeostatic Imbalances of the Muscular System

Hypertrophy of internal organs can sometimes be harmful. For example, hypertrophic cardiomyopathy, or HCM, is a disease of the heart muscle in which a portion of the cardiac muscle (usually the left ventricle) is enlarged without any obvious cause. HCM has been related to the sudden death of young athletes, but it is also of significance as a cause of sudden unexpected cardiac death in any age group and as a cause of disabling cardiac symptoms. Most patients' symptoms may be managed medically without needing surgery. HCM is not

Figure 21.38: Muscular paralysis and the resulting atrophy of the leg muscles, as this marathon racer with paraplegia has experienced, does not have to prevent a person from developing aerobic fitness.

to be confused with athletic heart syndrome which is hypertrophy of the heart muscle in response to exercise.

Delayed Onset Muscle Soreness (DOMS) is the pain or discomfort often felt 24 to 72 hours after exercising and generally goes away within 2 to 3 days. Once thought to be caused by lactic acid buildup, a more recent hypothesis is that it is caused by tiny tears in the muscle fibers caused by eccentric contraction, or an increased level of training. Since lactic acid is quickly taken away by in the blood, it cannot explain the pain experienced days after exercise. Delayed onset muscle soreness can occur after any kind of exercise, particularly if the body is unconditioned for that exercise.

Tendinitis is a painful disorder of a tendon. Generally tendinitis is referred to by the body part involved, such as Achilles tendinitis which affects the Achilles tendon, shown in **Figure** 21.39, or patellar tendinitis (jumper's knee, which affects the patellar tendon). It was believed that tendinitis was due to inflammation of a tendon, although this is now being questioned. Chronic overuse of tendons leads to microscopic tears within the collagen matrix, which gradually weakens the tissue. Eccentric muscle contractions are being researched for their ability to speed rehab of weak or injured tendons. Achilles tendinitis has been shown to benefit from high load eccentric contractions.

Neuromuscular diseases are those that affect the muscles and/or their nervous control. In general, problems with nervous control can cause spasticity or paralysis, depending on the location and nature of the problem. A large number of neurological disorders leads to problems with movement, ranging from strokes and Parkinson's disease, to the very rare and incurable degenerative disorder, Creutzfeldt-Jakob disease.

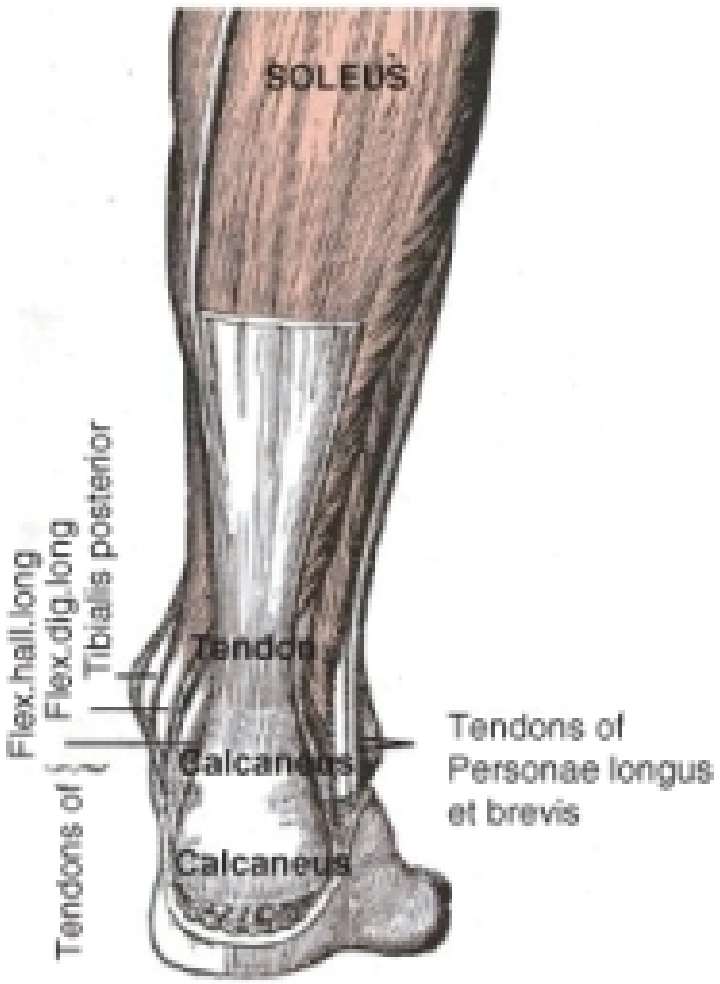

Figure 21.39: The Achilles tendon is a large tendon connecting the heel to the muscles of the calf.

Diseases of the motor end plate include myasthenia gravis, a form of muscle weakness due to antibodies to the acetylcholine receptor. Tetanus and botulism are bacterial intoxications in which bacterial toxins cause muscular spasms by blocking the action of inhibitory neurotransmitters (tetanus) or decreased muscle tone (botulism).

Myopathies are diseases affecting the muscle itself, rather than its nervous control. Muscular dystrophy is a large group of diseases which leads to progressive loss of muscle strength and decreased life span.

Smooth muscle plays a role in a large number of diseases affecting blood vessels, the respiratory tract (asthma), the digestive system (irritable bowel syndrome), and the urinary tract (urinary incontinence). However, these diseases are not usually confined just to the muscular tissue, and affect other tissues too.

Lesson Summary

- The human body has three types of muscle tissue: skeletal, smooth, and cardiac.
- One of the main characteristics of skeletal muscle tissue is its ability to contract. Nearly all movement in the body is the result of muscle contraction.
- Cardiac and skeletal muscles contain highly-regular arrangements of bundles of protein fibers that give them a striped appearance. Smooth muscle does not have such bundles of fibers, and so is not striated.
- In addition to movement, muscle contraction also fulfills some other important functions in the body, such as posture, joint stability, and heat production.
- Skeletal muscle fibers respond to the neurotransmitter acetylcholine.
- The thick myosin filament has small extensions or "heads," that "walk" along the thin actin filaments during a muscle contraction. In this way the thick filament slides over thin filament, and the muscle fiber shortens.
- Muscle fibers need ATP to contract and to relax.
- Muscle tissue is built up in the process of hypertrophy, and is lost in the process of atrophy.

Review Questions

1. Distinguish between striated and non-striated muscle.
2. Distinguish between voluntary and involuntary muscle.
3. Identify the three types of muscle in the body, and give an example of where each type is found.
4. Which type of muscle cell is multinucleated?
5. Is the quadriceps muscles in the leg an example of a smooth muscle? Explain your answer.
6. Which type of muscle cell metabolism results in the greater production of ATP, aerobic

or anaerobic? Give a reason for your answer.
7. Describe the components of a sacromere.
8. Distinguish between fast twitch and slow twitch muscle fibers.
9. After an athlete has completed a 100 meter sprint, his or her breathing rate will be greatly increased, and they need time to "catch their breath." Can you identify the process that leads to a person needing to catch their breath?

Further Reading / Supplemental Links

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- http://muscle.ucsd.edu/musintro/hypertrophy
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- http://www.nlm.nih.gov/medlineplus/ency/article/000688
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- http://training.seer.cancer.gov/module_anatomy/unit4_1_muscle_functions
- http://en.wikipedia.org

Vocabulary

actin A thread-like protein filament that is involved in muscle contraction.

aerobic respiration The breakdown of food energy to generate ATP, occurs in the presence of oxygen.

anaerobic glycolysis (anaerobic respiration) The breakdown of stored energy in the absence of oxygen to produce ATP.

atrophy The loss of muscle mass.

cardiac muscle Involuntary muscle that makes up the heart.

delayed onset muscle soreness (DOMS) The pain or discomfort often felt 24 to 72 hours after exercising and generally goes away within 2 to 3 days, caused by tiny tears in muscle fibers.

extensor A muscle that causes the angle of a joint to become larger.

flexor A muscle that causes the angle of a joint to become smaller.

hypertrophy The growth in size of muscle fibers and muscles.

isometric contraction Occurs when the muscle remains the same length despite building tension.

isotonic contraction Occurs when tension in the muscle remains constant despite a change in muscle length.

muscle contraction The generation of tension in a muscle fiber by the movement of actin and myosin.

motor unit A group of individual muscle fibers along with their motor neuron.

muscle fiber Long thin cell, composed of actin and myosin, that is able to contract.

myofibril Long cylindrical organelle that is made up of two types of protein filaments: actin and myosin.

myosin A protein filament that uses ATP to move along an actin filament, causing muscle contraction.

sarcomeres Repeating units of actin and myosin filaments.

skeletal muscle Used to move the body, usually attached to the skeleton, controlled voluntarily by the somatic nervous system and involuntarily through reflexes.

smooth muscle Found within the walls of organs and structures such as the esophagus, under involuntary control.

tendinitis A painful disorder of a tendon.

Points to Consider

- Identify ways in which damage to the integumentary system (for example, in a person with a severe burn) may affect the muscular and skeletal systems.
- Consider how the daily exercise routine and diet of an Olympic weightlifter would differ from that of a professional marathon runner.

21.3 Lesson 21.3: Integumentary System

Lesson Objectives

- Identify the structures that make up the integumentary system.
- Outline the role of the skin in providing a physical barrier to the external environment.
- Distinguish between the two layers that make up the skin.
- Identify two types of glands that are found in the skin.
- Outline the function of melanin.
- Outline the structure of hair.
- Examine the structure of nails, and compare them to the structure of nails.

Introduction

Your **integumentary system** is the external covering of your body. It is made up of your skin, hair, and nails. The integumentary system of other animals such as birds and reptiles includes their feathers and scales. The name comes from the Latin term *integumentum*, which means "a covering."

The integumentary system has multiple roles in homeostasis, including protection, temperature regulation, sensory reception, biochemical synthesis, and absorption. Keeping water out of the body is an important role for your integumentary system, as is shown by **Figure** 21.40. Your body systems all work together to maintain relatively stable internal conditions. Each of the parts that make up your integumentary system has a special role in maintaining homeostasis which we will explore a little later. An introduction to the Integumentary System can be viewed at http://www.youtube.com/watch?v=no_XRnoNGfE.

Structure and Function of Your Skin

The skin is a vital organ that covers the entire outside of the body, forming a protective barrier against pathogens and injuries from the environment. The skin is the body's largest organ, covering the entire outside of the body, and it is only about 2 mm thick. It shields the body against heat, light, injury, and infection. The skin also helps regulate body temperature, gathers sensory information from the environment, stores water, fat, and vitamin

Figure 21.40: Your skin acts like a waterproof barrier so that you can swim without water leaking into your body.

D, and acts as a physical barrier in protecting us from disease.

Your skin is constantly in contact with your external environment so it gets cut, scratched, and exposed to radiation, such as ultraviolet (UV) light. You also naturally shed many skin cells every day. Your body replaces damaged or missing skin cells by growing more of them, through the process of mitosis. Two distinct layers make up the skin: the epidermis and the dermis. A fatty layer, called subcutaneous tissue, or hypodermis (below skin), lies under the dermis, but it is not considered to be part of your skin. The layers that make up your skin are shown in **Figure** 21.41.

The color, thickness and texture of skin vary over the body. There are two general types of skin; thin and hairy, which is the most common type on the body, and thick and hairless, which is found on parts of the body that are used heavily and experience a lot of friction, such as the palms of the hands or the soles of the feet.

Epidermis

Epidermis is the outermost layer of the skin. It forms the waterproof, protective wrap over the body's surface and is made up of many layers of epithelial cells, shown in **Figure** 21.42.

The epidermis is divided into several layers where epithelial cells are formed through mitosis in the lowest layer. The epithelial cells move up through the layers of the epidermis, changing shape and composition as they differentiate and become filled with a tough, fibrous protein called keratin. At this point the cells are called keratinocytes. Keratinocytes at the surface of the epidermis form a thin layer of flattened, dead cells, (the stratum corneum in **Figure** 21.42). Although the top layer of epidermis is only about as thick as a sheet of paper, it is

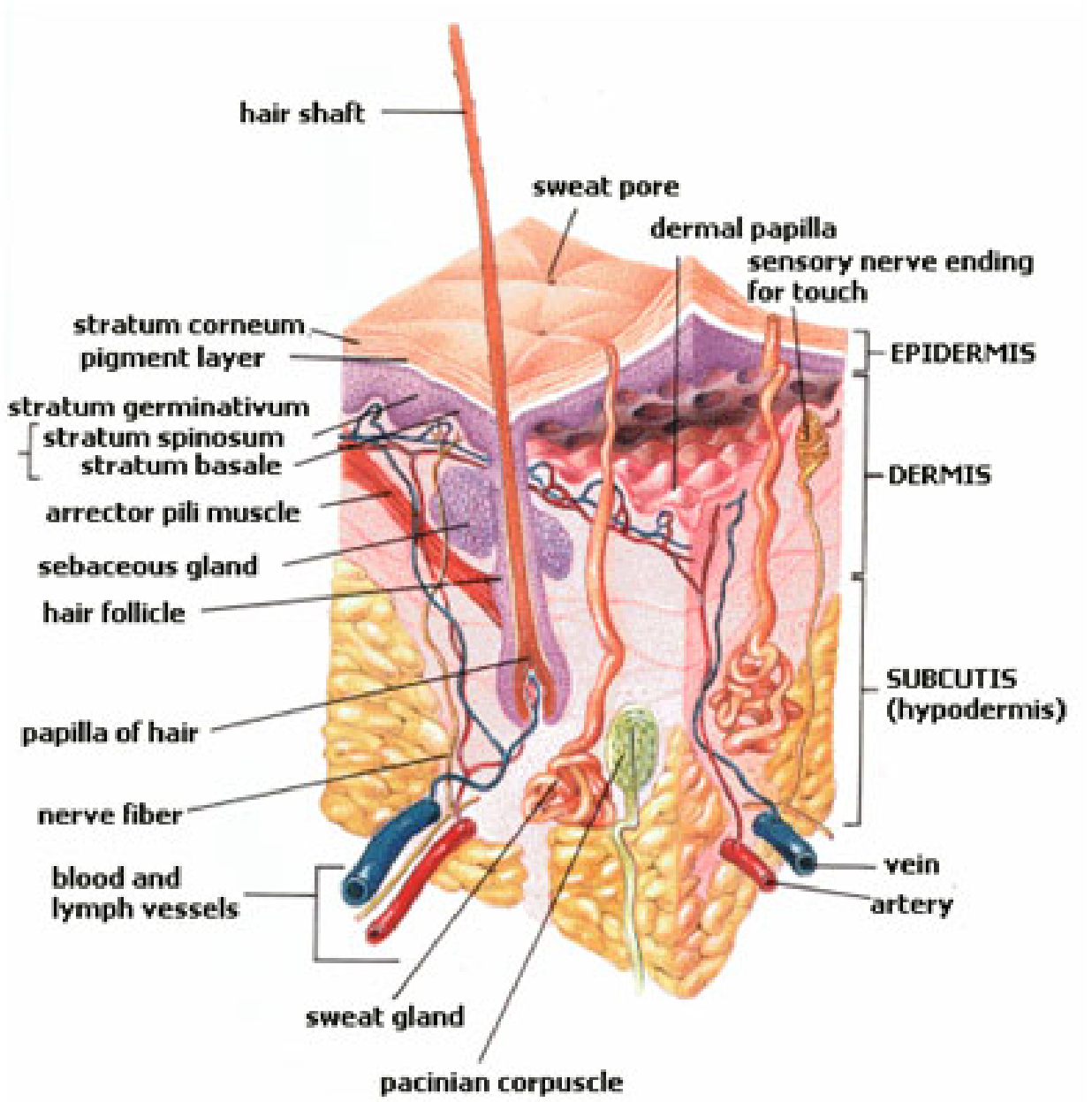

Figure 21.41: Structure of the skin. The structures of the epidermis, dermis, and the subcutaneous tissue (called the subcutis in this diagram). Note how there are no blood vessels in the epidermis.

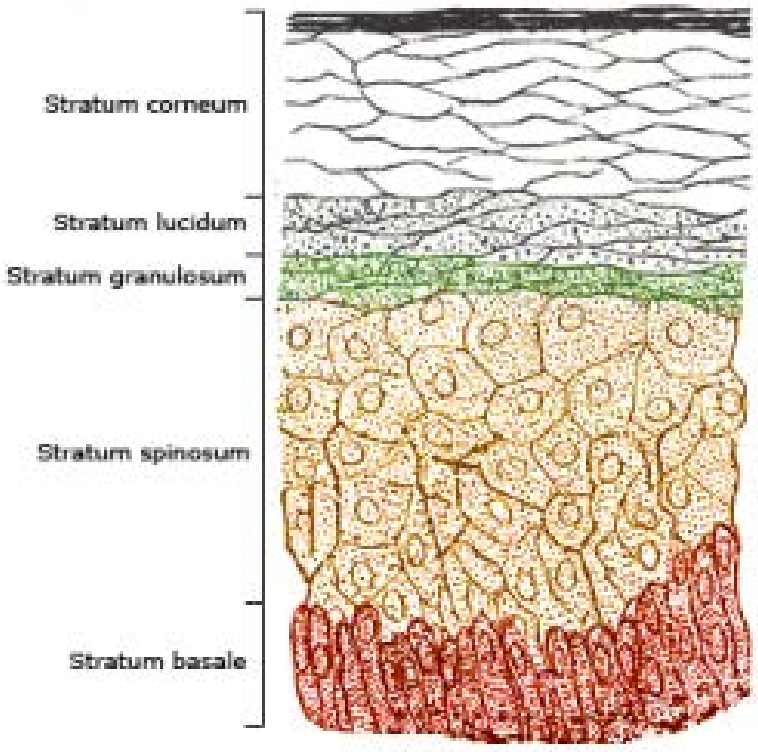

Figure 21.42: The epidermis is made up of many layers of epithelial cells. The uppermost layer is made up of many flat, dead, keratin-filled cells called keratinocytes. Every day, thousands of keratinocytes get scraped off the surface of your skin, and are replaced by cells that move up from lower layers.

made up of 25 to 30 layers of keratinocytes. Keratinocytes get scraped off through everyday activities, and are usually shed about a month after they reach the surface of the epidermis.

The epidermis also contains cells called melanocytes that produce the pigment melanin. **Melanin** is the brownish pigment that gives skin and hair their color. **Melanocytes** are located in the bottom layer of the epidermis, the stratum basale, shown in **Figure** 21.42. The difference in skin color between light-skinned people and dark-skinned people is not due to the number of melanocytes in their skin, but to the melanocytes' level of activity. The amount of melanin produced in a person's skin is dependent on his or her genetics and the amount of ultraviolet (UV) light exposure. Melanin absorbs UV rays from the sun or other sources of UV light, such as a tanning bed. When UV light penetrates the skin and damages DNA; the damaged DNA triggers the synthesis of more melanin. The skin also makes vitamin D by absorbing energy from UV light. Melanin acts like a UV filter, so the more melanin in a person's skin, the more time the person has to spend in sunlight to produce the same amount of vitamin D as a person with less melanin in their skin.

The epidermis also contains cells that take up and process certain marker proteins (called antigens) from microbes that enter through the skin. This helps the immune system recognize the microbe as an intruder, and to mount an attack on it. The epidermis contains no blood vessels, so the lower portion of the epidermis is nourished by diffusion from the blood vessels of the dermis.

Structure and Function of Dermis

The **dermis** is the layer of skin directly under the epidermis and is made of a tough elastic connective tissue. The dermis is tightly connected to the epidermis by a membrane made of collagen fibers. The dermis contains the hair follicles, sweat glands, sebaceous glands, and blood vessels. It also holds many nerve endings that provide the sense of touch, pressure, heat, and pain. Tiny muscles, called arrector pili, contract and pull on hair follicles which cause hair to stand up. This can happen when you are cold or afraid, and the resulting little "bumps" in the skin are commonly called goose bumps.

The dermis has two layers, each of which contains different structures:

Papillary region (upper layer): The papillary region is made up of loose connective tissue and contains touch receptors which communicate with the central nervous system. It is named for its finger-like projections called papillae, which extend toward the epidermis, and help secure the dermis to the epidermis. The papillae can be seen in **Figure** 21.41. The papillae provide the dermis with a "bumpy" surface that causes distinctive friction ridges. They are called friction ridges, because they help the hand or foot to grasp things by increasing friction. Friction ridges, as shown in **Figure** 21.43, occur in patterns that are unique to the individual, making it possible to use fingerprints or footprints as a means of identification.

Figure 21.43: Close-up image of a toe print. The friction ridges that originate in the dermis and make up the whorls and lines of finger and toe prints are clearly visible. Both fingers and toes have these distinctive ridges.

Reticular region (lower layer): The reticular region is made of dense elastic fibers (collagen), which contains the hair follicles and roots, nerves, and glands. It gets its name from the dense concentration of protein fibers that weave throughout it. These protein fibers give the dermis its properties of strength, extensibility, and elasticity. Heat, cold and pressure receptors, nails, and blood vessels are also located in this region. Tattoo ink is injected into the dermis. Stretch marks are also located in the dermis.

Glands and Follicles

Glands and follicles open out into the epidermis, but they originate within the dermis. A **sebaceous gland**, also known as an oil gland, secretes an oily substance, called sebum, into the hair follicle. **Sebum** is made of lipids and the debris of dead lipid-producing cells. The word sebum comes from the Latin word for fat, or tallow. It "waterproofs" hair and the skin surface to prevent them from drying out. It can also inhibit the growth of microorganisms on the skin. Sebum is the cause of the oily appearance of skin and hair. It is odorless, but the breakdown of sebum by bacteria can cause odors. A sebaceous gland is shown in **Figure** 21.44. If a sebaceous gland becomes plugged and infected, it develops into a pimple, also called acne.

Sweat glands open to the epidermal surface through the skin pores. They occur all over the body and are controlled by the sympathetic nervous system. Evaporation of sweat from

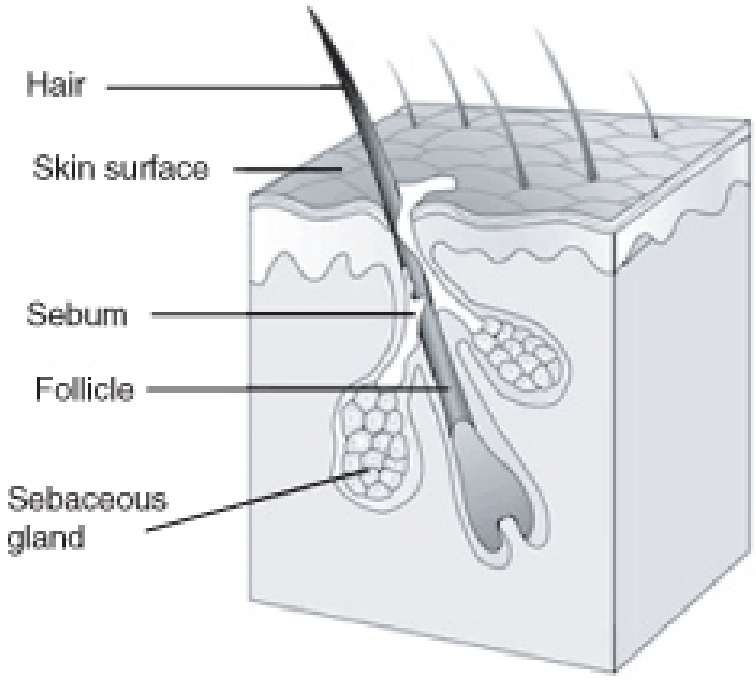

Figure 21.44: A sebaceous gland an associated hair follicle. Sebum acts to protect and waterproof hair and skin, and keep them from becoming dry, brittle and cracked.

the skin surface helps to lower the skin temperature, which in turn helps to control body temperature. The skin also functions as an excretory organ because it releases excess water, salts, and other wastes in sweat. A sweat gland is shown in **Figure** 21.45. There are two types of sweat glands, eccrine glands and apocrine glands. Eccrine glands are the "regular" sweat glands that release sweat to cool the body. Apocrine glands are larger than eccrine glands and are located in the armpits and groin areas. They effectively act as scent glands because they produce a solution that bacteria break down which produces "body odor."

Mammary glands are the organs that, in the female mammal, produce milk to feed their young. Mammary glands are enlarged and modified sweat glands and are a major characteristic of mammals.

Subcutaneous Tissue

The **subcutaneous tissue** (also called the hypodermis), lies below the dermis and contains fat and loose connective tissue that holds larger blood vessels and nerves. Its purpose is to attach the skin to underlying bone and muscle as well as to supply the skin with blood vessels and nerves. This layer is important is the regulation of body temperature. It is mostly made up of adipose tissue (which is made up of fat cells or adipocytes); the subcutaneous tissue contains about 50 percent of the body's fat. The functions of subcutaneous tissue include

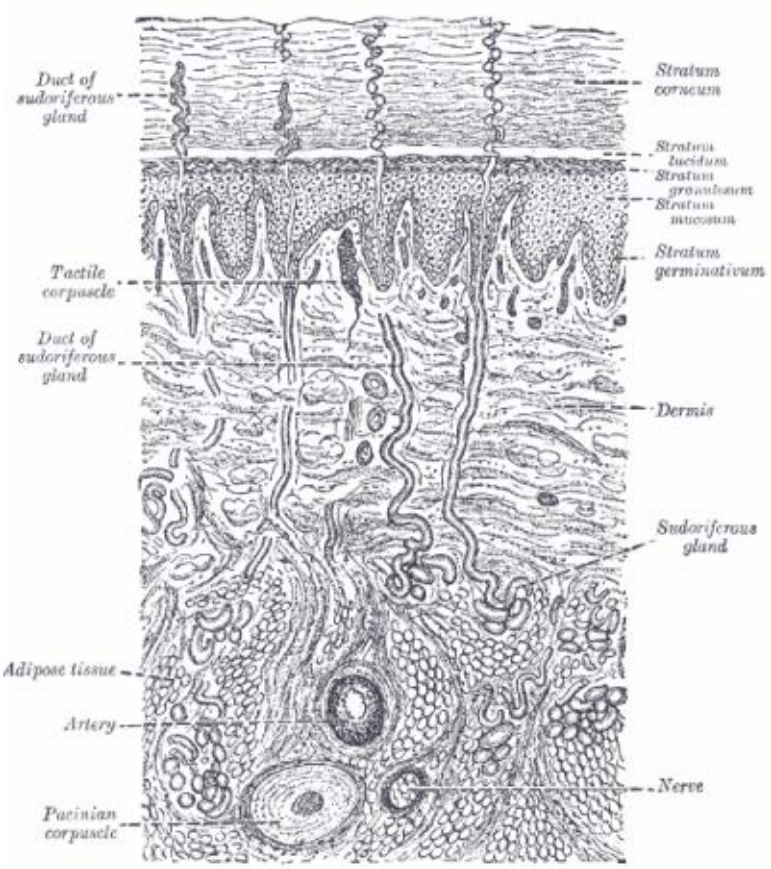

Figure 21.45: Location of sweat glands in the dermis. Note that the sweat glands are called sudoriferous glands in this image.

insulation and the storage of nutrients. The size of this layer varies throughout the body and from person to person.

Functions of Skin: Skin and Homeostasis

The skin has multiple roles in homeostasis, including protection, control of body temperature, sensory reception, water balance, synthesis of vitamins and hormones, and absorption of materials. The skin's main functions are to serve as a barrier to the entry of microbes and viruses, and to prevent water and extracellular fluid loss. Acidic secretions from skin glands also stop the growth of fungi on the skin. Melanocytes form a second barrier: protection from the damaging effects of UV radiation. When a microbe gets into the skin (or when the skin is cut) an immune system reaction occurs.

Heat and cold receptors are located in the skin. When the body temperature rises, the hypothalamus sends a nerve signal to the sweat-producing skin glands, causing them to release sweat onto the skin surface. The evaporation of sweat helps reduce the temperature of the skin surface which cools the body. The hypothalamus also causes dilation of the blood vessels of the skin, allowing more blood to flow into those areas, causing heat to be released from the skin surface. When body temperature falls, the sweat glands constrict and sweat production decreases. If the body temperature continues to fall, the body will start to generate heat by raising the body's metabolic rate and by causing the muscles to shiver.

The homeostatic functions of the skin include:

- Protection of the body's internal tissues and organs.
- Protection against invasion by infectious organisms.
- Protection of the body from dehydration.
- Protection of the body against large changes in temperature.
- Excretion of wastes through sweat.
- Acts as a receptor for the senses of touch, pressure, pain, heat, and cold.
- Makes vitamin D through exposure to UV radiation.
- Stores water, fat, and vitamin D.

Homeostatic Imbalances of the Skin

Many wavelengths of electromagnetic radiation are emitted by the sun, some we can see, and others we cannot. The range of wavelengths of radiation we can see is called visible light. However, visible light makes up only a small portion of the total radiation that comes from the sun. Two other types of radiation that you have probably heard about before include infrared and ultraviolet radiation. Infrared light is the thermal energy, or the "heat rays" that you feel when the sun shines on you. The other, ultraviolet (UV), which we have discussed a little already, helps the body produce vitamin D, but it can also damage DNA in skin cells. Our main source of UV radiation, the sun, is shown in **Figure** 21.46.

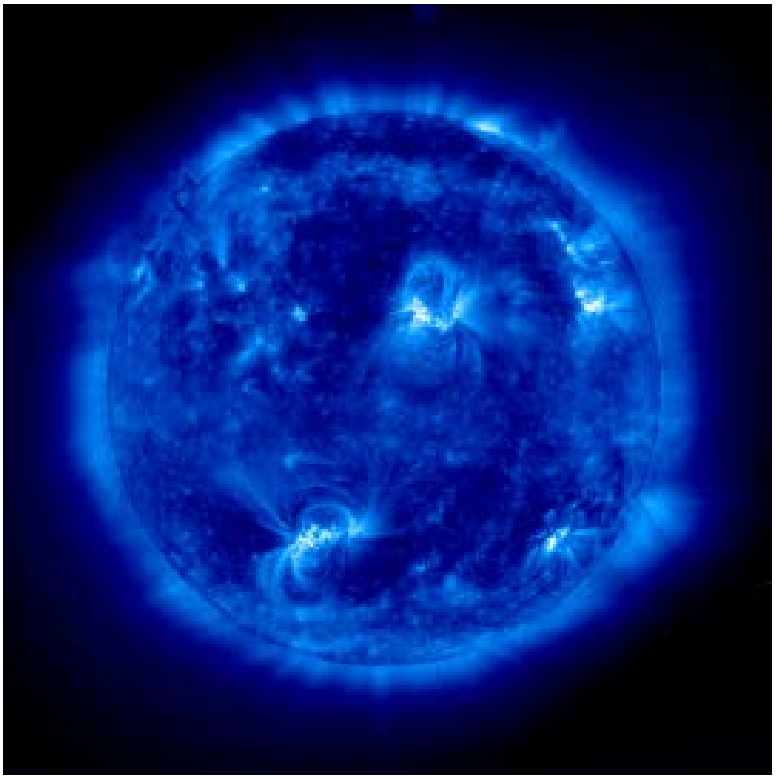

Figure 21.46: Ultraviolet radiation emitted by the sun. Prolonged exposure to UV radiation can lead to skin cancer and premature wrinkling of the skin.

Beneficial Effects of UV Radiation

A positive effect of ultraviolet radiation (UV) exposure is that it causes the production of vitamin D in the skin. It has been estimated that tens of thousands of premature deaths occur in the United States annually from a range of cancers due to vitamin D deficiency.

Ultraviolet radiation has other medical applications, in the treatment of skin conditions such as psoriasis, a disorder in which red, scaly patches form due to an overproduction of epithelial cells, and vitiligo, a condition that causes loss of pigment, which results in irregular pale patches of skin, as shown in **Figure** 21.47.

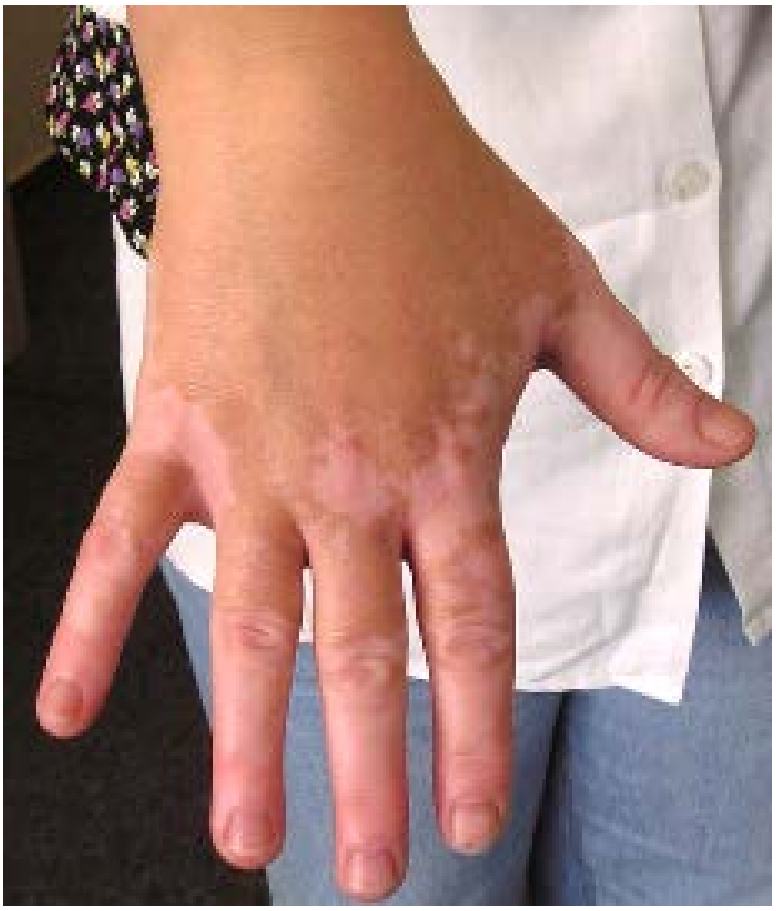

Figure 21.47: Vitiligo is chronic skin condition that causes loss of pigment, resulting in irregular pale patches of skin. The cause of vitiligo is not fully understood. There is some evidence suggesting it is caused by a combination of auto-immune, genetic, and environmental factors. Phototherapy in which the patient is exposed to long-wave ultraviolet (UVA) light from the sun or from UVA lamps, together with certain medicines, can help in many cases.

Harmful Effects of UV Radiation

In humans, prolonged exposure to solar UV radiation may result in acute and chronic health effects on the skin, eye, and immune system. While some sunlight is good for health, skin cancer caused by excessive exposure to sunlight is not among the sun's benefits. Because some types of skin cancer are easy to cure, the danger posed by too much sunlight is perhaps not taken seriously enough. It is important to remember that a more serious form of skin cancer, called melanoma, is also associated with excessive sun exposure. Melanomas are potentially lethal tumors.

The UV radiation excites DNA molecules in skin cells, causing bonds to form between neighboring thymine bases, producing a thymine dimer that changes the shape of the DNA helix. These dimers can lead to mutations. **Mutations** are changes to the base pair sequence of DNA or RNA. Mutations can result in cancerous growths.

Skin cancer is an increasingly common condition. This is due in part to peoples' increased exposure to UV radiation, because of the increased popularity of sun bathing. Because melanin protects the skin from the effects of UV radiation, lighter-skinned people are at more risk of developing skin cancer than darker skinned people are. However, the risk of developing skin cancer is related to the amount of sunburn and overall length of time a person has been exposed to UV light. The three most common types of skin cancers are shown in **Figure** 21.48.

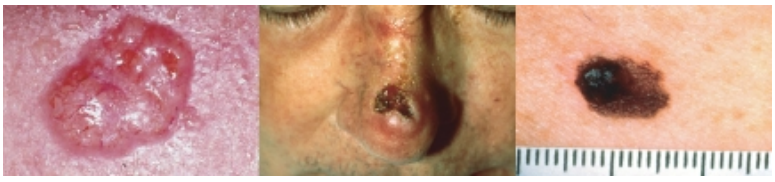

Figure 21.48: The three most common forms of skin cancer. Basal cell carcinoma (left), squamous cell carcinoma (center), and melanoma (right). All three types arise from cells in the epithelium.

As a defense against UV radiation, the body tans when exposed to moderate levels of radiation by releasing the brown pigment melanin. This helps to block UV penetration and prevent damage to the vulnerable skin tissues deeper down. Suntan lotion, often referred to as "sun block" or "sunscreen", partly blocks UV and is widely available. Most of these products contain a sun protection factor (SPF) rating that describes the amount of protection given. This protection, however, applies only to a type of UV radiation called UVB rays, the type of radiation that is responsible for sunburn. UVA rays, another type of UV radiation, penetrates more deeply into the skin and may be responsible for causing cancer and wrinkles. Some sunscreen lotion now includes compounds such as titanium dioxide which helps protect against UVA rays. Other UVA blocking compounds found in sunscreen include zinc oxide and avobenzone. Another means to block UV is sun protective clothing, shown in **Figure**

21.49. This is clothing that has an ultraviolet protection factor (UPF) rating that describes the protection given against both UVA and UVB radiation.

Figure 21.49: Some good advice from the National Cancer Institute. The risk of melanoma and other forms of skin cancer can be significantly reduced by avoiding excessive exposure to the sun, using sunscreen lotions, and wearing protective clothing to shield the skin from ultraviolet radiation.

Acne

The most common form of acne is known as acne vulgaris, which means "common acne." Many teenagers get this type of acne. Acne is a highly complicated and variable form of skin infection. It affects more than 85% of teenagers, but frequently also continues into adulthood. For most people, acne tends to decrease or disappear after one reaches his or her early twenties. Excessive secretion of sebum from the sebaceous glands leads to the plugging of the hair follicle with dead skin cells (corneocytes). This blockage is caused by a failure of the normal process in which skin cells that line the pores are usually shed. Within these blocked pores bacteria and yeast begin to multiply. In response to the bacterial and yeast populations, the skin inflames, which produces a red bump.

Nails and Hair

Nails are made up of specialized epidermal cells. Fingernails and toenails contain a tough protein called keratin and are actually a type of modified hair. The nail grows from the nail bed, which is thickened to form a lunula (or little moon), shown in **Figure** 21.50. Cells

forming the nail bed are linked together to form the nail. There are no nerve endings in the nail.

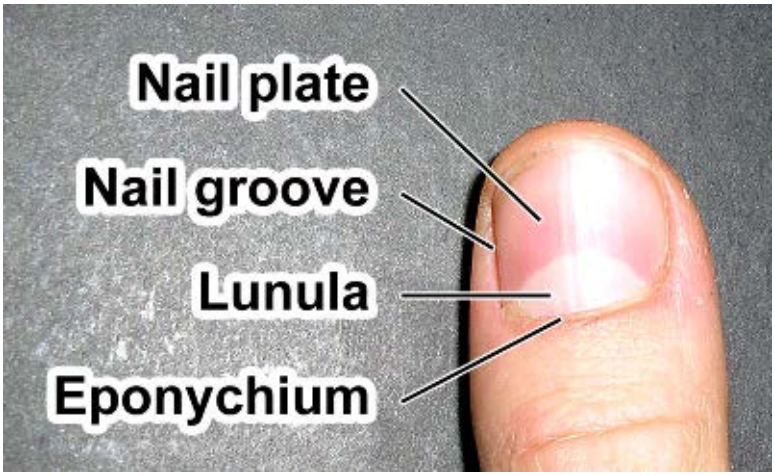

Figure 21.50: The parts of the nail. The lunula is also called the little moon, the eponychium is also called the cuticle.

The fingernail generally serves two purposes. It serves as a protective plate and enhances sensation of the fingertip. The protection function of the fingernail is commonly known, but the sensation function is equally important. The fingertip has many nerve endings in it allowing us to receive volumes of information about objects we touch. The nail acts as a counterforce to the fingertip providing even more sensory input when an object is touched.

Nails are made up of many different parts, as shown in **Figure** 21.50:

- The free edge is the part of the nail that extends past the finger, beyond the nail plate.
- The nail plate is what we think of when we say "nail," the hard and translucent portion, composed of keratin.
- The lunula is the crescent shaped whitish area of the nail bed (when visible).
- The eponychium or cuticle, is the fold of skin at the end of the nail.

Nails grow at a rate about 1 cm every 100 days. Fingernails require 4 to 6 months to regrow completely and toenails require 12 to 18 months. Actual growth rate is dependent upon age, season, exercise level, and hereditary factors. This growth record can show the history of recent health and physiological imbalances, and has been used as a diagnostic tool since ancient times.

Major illness will cause a deep horizontal groove to form in the nails. Discoloration, thinning, thickening, brittleness, splitting, grooves, spots, lines, receded lunula, or changes in the shape of the nail can indicate illness in other areas of the body, nutrient deficiencies, drug reaction or poisoning, or a physical injury to the nail or nail bed.

Hair

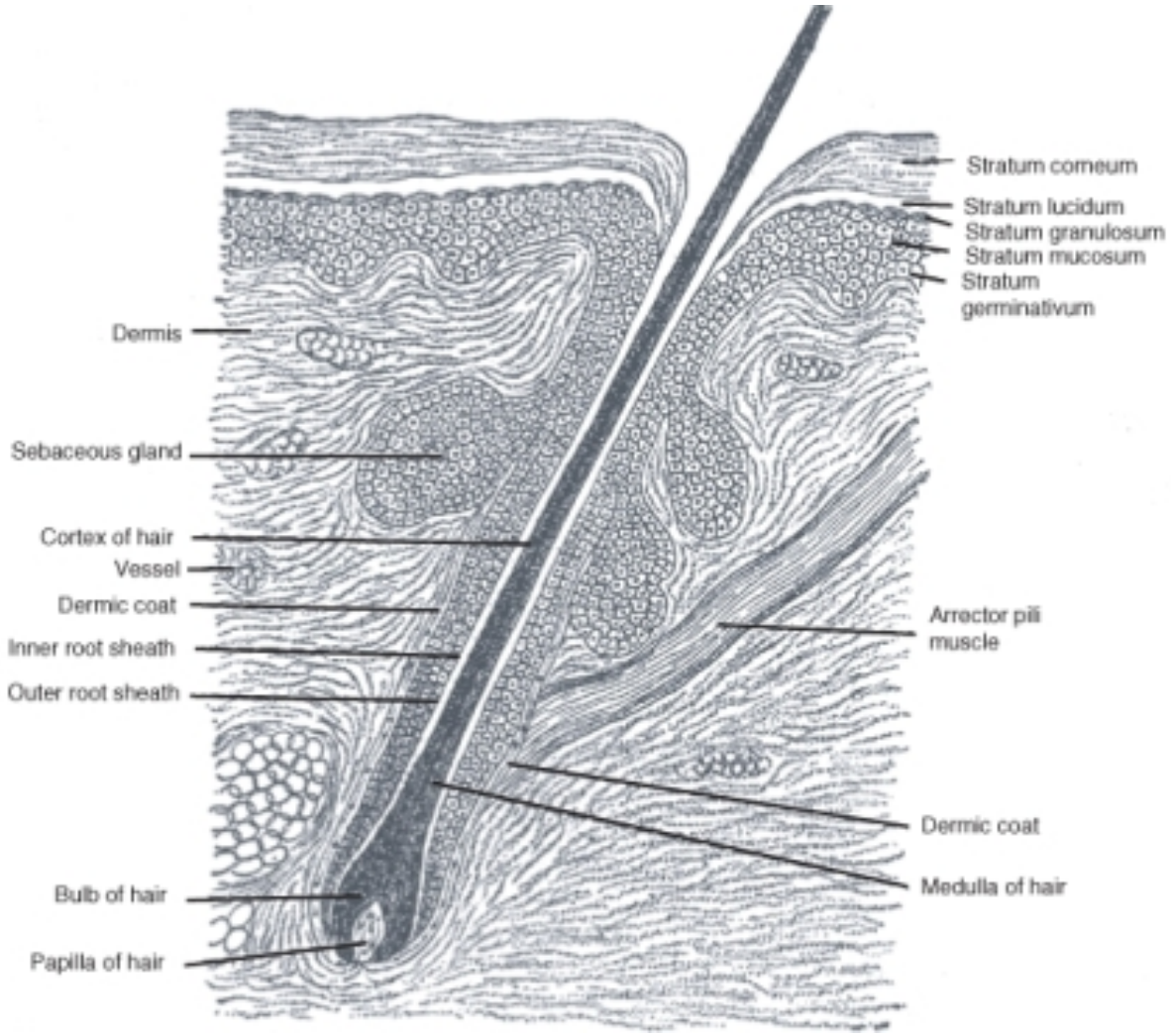

Figure 21.51: A hair follicle and hair.

Hair is a filamentous fiber that is found only on mammals. The main component of hair is the tough protein keratin. Hair emerges from the epidermis, although it grows from hair follicles deep in the dermis, shown in **Figure** 21.51. The hair of non-human mammal species is commonly called fur.

Humans have three different types of hair:

- Lanugo is the fine hair that covers nearly the entire body of fetuses.
- Vellus hair is the short, fine, "peach fuzz" body hair that grows in most places on the human body except for the palms of the hands and the soles of the feet.

- Terminal hair is the fully developed hair which is generally longer, coarser, thicker, and darker than vellus hair.

Different parts of the human body have different types of hair. From childhood onward, vellus hair covers the entire human body except on the lips, the palms of hands, the soles of feet, the navel, and scar tissue. The density of the hairs (in hair follicles per square centimeter) varies from one person to another.

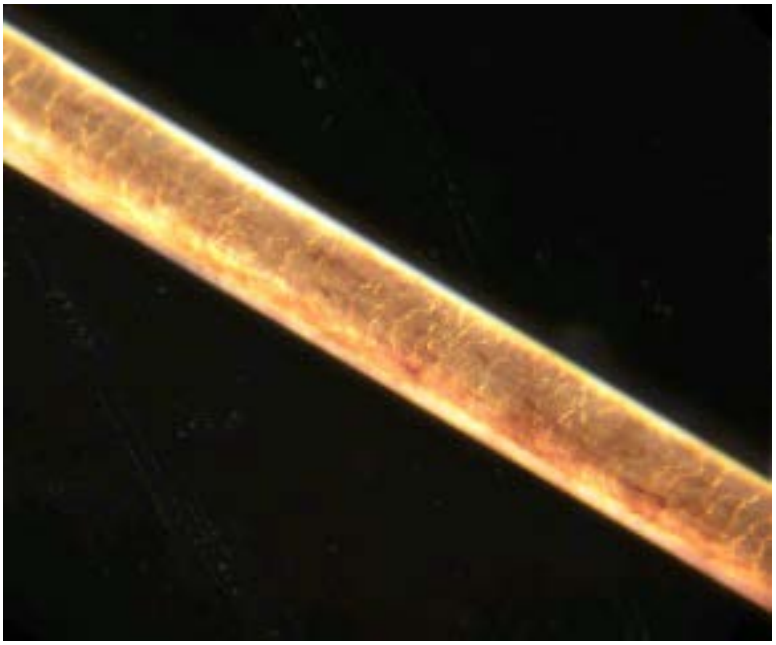

Figure 21.52: Magnification of a human hair. The hair shaft is composed of dead, keratin-filled (keratinized) skin cells that overlap each other like the shingles, or tiles on a roof. You can see the overlapping cells in this image.

What is the function of hair? In people, hair serves to insulate, to protect, and to sense the immediate surroundings. Insulation serves to conserve heat. The hair on your head insulates your body from heat loss. Eyelashes and eyebrows protect the eyes from water, dirt, and other irritants. Nose hairs act as a physical barrier to any particles or microorganisms that might be in the air we breathe.

Curly hair has a different biological structure than straight hair, shown in **Figure** 21.52. It tends to be much drier than straight hair because the oils secreted into the hair shaft by the sebaceous glands can more easily travel down the shaft of straight hair. People with very curly hair may find that this hair type can be dry, hard to manage, and often frizzy.

Individual hairs have periods of growth and dormancy. During the growth portion of the cycle, hair follicles are long and bulbous, and the hair grows out at about a third of a millimeter per day. After three to six months, body hair growth stops (the pubic and armpit

areas having the longest growth period). The follicle shrinks and the root of the hair grows rigid. Following a period of dormancy, another growth cycle starts, and eventually a new hair pushes the old one out of the follicle from beneath. Head hair, by comparison, grows for a long duration and to a great length before being shed. Terminal hair is genetically programmed to be straight, curly or wavy, and it tends to change over time.

Hair color is the result of pigmentation due to the presence of different forms of melanin. In general, the more melanin present, the darker the hair color; the less melanin, the lighter the hair color. A person's hair color may also change over time and may be more than one color at a time.

Lesson Summary

- The integumentary system consists of the skin, hair, and nails.
- The skin is the covering of the body. It acts as a physical barrier to the external environment.
- The outermost layer, of the skin, the epidermis, consists of many layers of dead keratinized skill cells. The epidermis is waterproof and prevents fluids from leaking out of the body and into the body.
- The dermis is the layer of skin directly under the epidermis and is made of a tough elastic connective tissue. The dermis is tightly connected to the epidermis by a membrane made of collagen fibers.
- Glands and follicles open out into the epidermis, but they originate within the dermis. A sebaceous gland or oil gland secretes an oily substance, called sebum, into the hair follicle. Sweat glands open to the epidermal surface through the skin pores. They occur all over the body and are controlled by the sympathetic nervous system.
- Melanin is the brownish pigment that gives skin and hair their color. It is found in melanocytes are located in the bottom layer of the epidermis. Melanin acts as a UV filter, it absorbs UV rays from the sun or other sources of UV light, such as a tanning bed.
- The main component of hair and nails is the tough protein keratin.

Review Questions

1. Name all of the parts of the integumentary system.
2. Name the two layers that make up the skin, and identify a function for each layer.
3. Why is subcutaneous tissue also called *subdermal tissue*?
4. Why is the epidermis considered the dead part of the skin?
5. Name the cells that produce melanin and describe where they are found.
6. Explain how sweating helps regulate body temperature. **Use** Figure **21.53 of part of the integumentary system to answer questions 7 and 8.**
7. In what layer of the skin would you find this tissue?

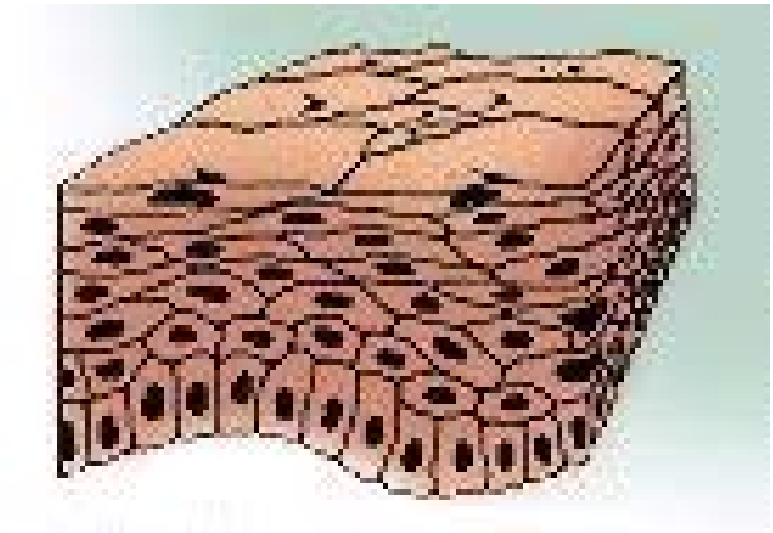

Figure 21.53

8. Name the substance that is found in the uppermost layer of this tissue.
9. Describe one function of hair.
10. Identify the substance that prevents skin and hair from drying out.

Further Reading / Supplemental Links

- Anatomy and Physiology © 2002 Elaine Marieb. Published by Pearson Education Inc. as Benjamin Cummings.
- http://training.seer.cancer.gov/ss_module14_melanoma/unit02_sec01_anatomy
- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookINTEGUSYS
- http://www.cancer.gov/cancertopics/understandingcancer/environment
- http://www.cancer.gov/cancertopics/understandingcancer/cancer/Slide54
- http://animaldiversity.ummz.umich.edu/site/topics/mammal_anatomy/hair
- http://www.cancer.gov/cancertopics/understandingcancer/cancer
- http://www.cdc.gov/excite/skincancer/index
- http://www.niams.nih.gov/hi/topics/acne/acne
- http://en.wikipedia.org

Vocabulary

dermis The layer of skin directly under the epidermis, contains the hair follicles, sweat glands, sebaceous glands, and blood vessels.

epidermis The outermost layer of the skin.

integumentary system The organ system consisting of your skin, hair and nails.

melanin The brown pigment that gives skin, hair and eyes their color.

melanocytes Cells that produce melanin, found in the skin, hair and eyes.

mutation A change to the nucleotide sequence of DNA or RNA.

papillary region Part of the dermis that contains touch receptors, which communicate with the central nervous system.

reticular region Part of the dermis that contains the hair follicles and roots, nerves, and glands.

sebaceous gland Secretes an oily substance, called sebum, into the hair follicle.

sebum An oily substance secreted by sebaceous glands that is composed of lipids and debris of dead lipid-producing cells, responsible for protecting the skin and hair against drying out, and infection by microorganisms.

subcutaneous tissue (hypodermis) Lies below the dermis and contains fat and loose connective tissue that holds larger blood vessels and nerves, attaches the skin to underlying bone and muscle.

Points to Consider

- Identify reasons why you should wear sunblock with an SPF value of at least 15 everyday.
- Consider what might happen if hair, fingernails and toenails contained sensory receptors.

Image Sources

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Chapter 22

Circulatory and Respiratory Systems

22.1 Lesson 22.1: Circulatory System

Lesson Objectives

- Identify the functions and components of the cardiovascular system.
- Describe the structure of the heart.
- Outline the flow of blood through the heart.
- Compare the structures of arteries, veins, and capillaries.
- Compare pulmonary circulation and systemic circulation.
- Outline the functions of the lymphatic system.
- Describe the importance of the coronary arteries.
- Outline the process of atherosclerosis.
- Describe ways of preventing cardiovascular diseases.

Introduction

The **cardiovascular system** shown in **Figure** 22.1 is an organ system that moves nutrients, hormones, gases and wastes to and from body cells, and distributes heat to maintain homeostasis. The main components of the cardiovascular system are the heart, the blood vessels, and the blood.

The Heart

The **heart** is the muscular organ that pumps blood through the blood vessels by repeated, rhythmic contractions. The term cardiac means ”related to the heart” and comes from the Greek word *kardia*, for ”heart.” The heart is made up mostly of cardiac muscle tissue, (shown

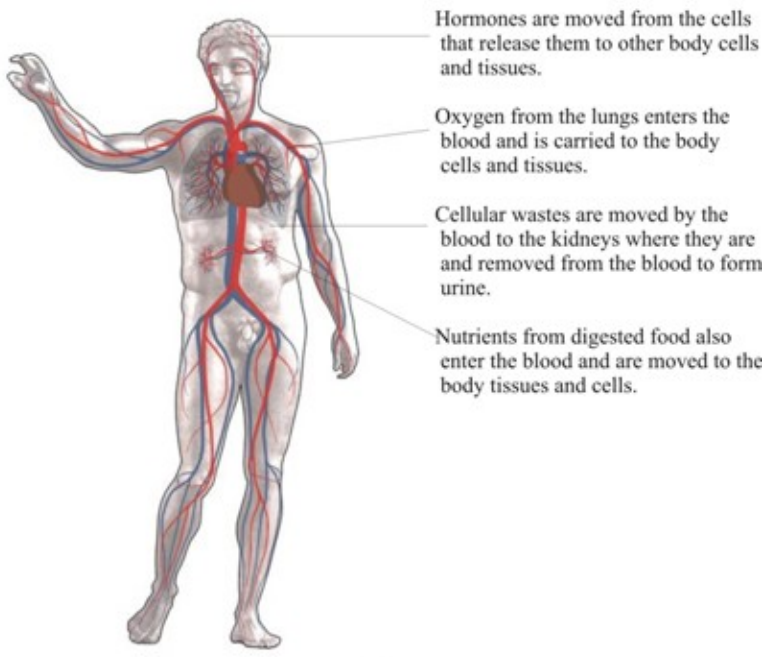


Figure 22.1: The main organs of the circulatory system. Blood acts as the transporter in the body, while blood vessels act like little (one way) roads. The figure is Michelangelo's marble sculpture David, which does not actually have a circulatory system.

in **Figure** 22.2) which contracts to pump blood around the body. In adults, the normal mass of the heart is 250-350 grams (9-12 oz), or about three quarters the size of a clenched fist, but badly diseased hearts can be up to 1000 g (2 lb) in mass due to enlargement of the cardiac muscle. For an animation of the heart's anatomy, see http://www.byrnehealthcare.com/animations/SutterAnatomy.htm.

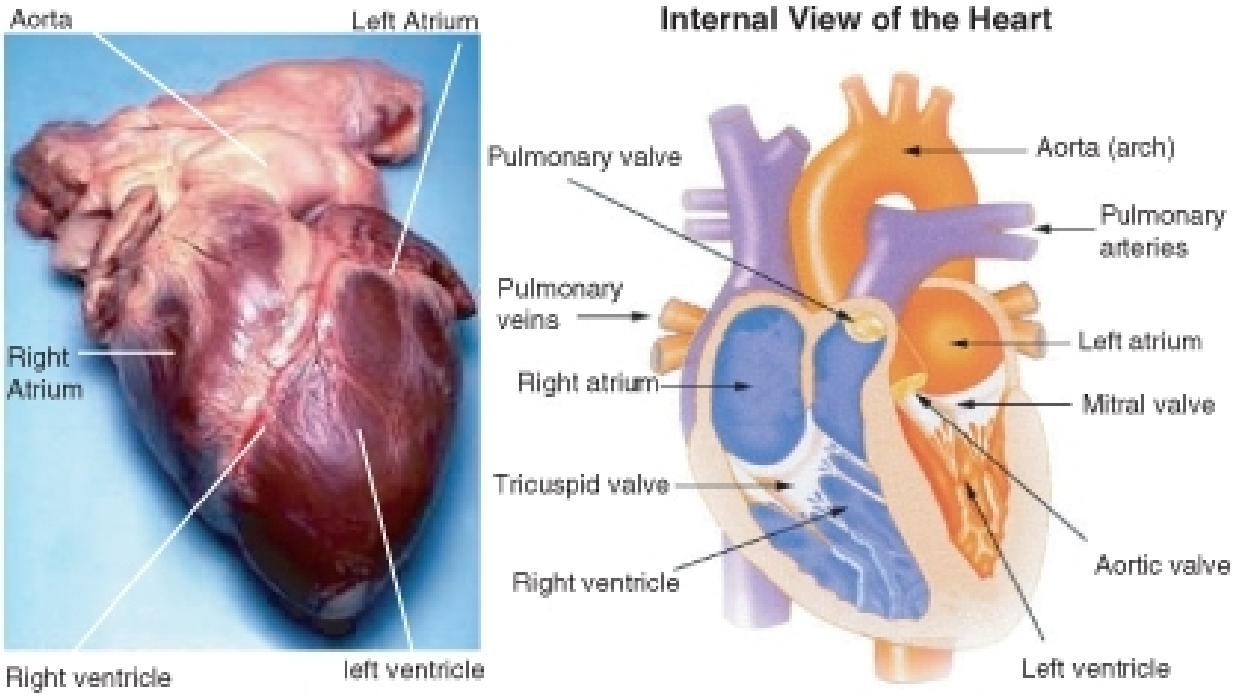


Figure 22.2: External and internal views of the human heart. The aorta in the photo cannot be seen clearly because it is covered by a layer of adipose tissue (fat).

The heart is usually found in the left to middle of the chest with the largest part of the heart slightly to the left. The heart is usually felt to be on the left side because the left ventricle is stronger (it pumps to all the body parts). The heart is surrounded by the lungs. The left lung is smaller than the right lung because the heart takes up more room in the left side of the chest. The position of the heart within the chest is shown in **Figure** 22.3.

Blood Flow Through the Heart

Blood flows through the heart in two separate loops; you could think of them as a "left side loop" and a "right side loop." The right side and left side of the heart refer to your heart as it sits within your chest. Its left side is your left side and, its right side is your right side.

The right side of the heart collects deoxygenated blood from the body and pumps it into the lungs where it releases carbon dioxide and picks up oxygen. The left-side carries the

Figure 22.3: Position of the heart in relation to the lungs. The heart can be seen in the lower middle area of the figure, behind the lungs.

oxygenated blood back from the lungs, into the left side of the heart which then pumps the oxygenated blood throughout the rest of the body.

The heart has four chambers, the two upper atria and the two lower ventricles. **Atria** (singular, atrium) are the thin-walled blood collection chambers of the heart. Atria pump the blood into the ventricles. **Ventricles** are the heart chambers which collect blood from the atria and pump it out of the heart. On the right side of the heart, deoxygenated blood from the body enters the right atrium from the superior vena cava and the inferior vena cava, shown in **Figure** 22.4. Blood enters the right ventricle which then pumps the blood through the pulmonary arteries and into the lungs. In the lungs, carbon dioxide is released from the blood and oxygen is picked up.

Pulmonary veins bring the oxygenated blood back to the heart and into the left atrium. From the left atrium the blood moves to the left ventricle which pumps it out to the body through the aorta. On both sides, the lower ventricles are thicker and stronger than the upper atria. The muscle wall surrounding the left ventricle is thicker and stronger than the wall surrounding the right ventricle because the left ventricle needs to exert enough force to pump the blood through the body. The right ventricle only needs to pump the blood as far as the lungs, which does not require as much contractile force.

Valves in the heart maintain the flow of blood by opening and closing in one direction only. Blood can move only forward through the heart, and is prevented from flowing backward by the valves. Such movement of the blood is called unidirectional flow. There are four valves of the heart:

- The two **atrioventricular (AV) valves** ensure blood flows from the atria to the ventricles, and not the other way. The AV valve on the right side of the heart is called the tricuspid valve, and the one on the left of the heart is called the mitral, or bicuspid valve.

- The two **semilunar (SL) valves** are present in the arteries leaving the heart, and they prevent blood flowing back from the arteries into the ventricles. The SL valve on the right side of the heart is called the pulmonary valve, because it is leads to the pulmonary arteries, and the SL valve on the left is called aortic valve because it leads to the aorta. The valves of the heart are shown in **Figure** 22.4.

The Heartbeat

The heart is a meshwork of cardiac muscle cells that are interconnected by little channels called gap junctions. This interconnection allows the electrical stimulation of one cell to spread quickly to its neighboring cells. Cardiac muscle is self-exciting. This is in contrast to skeletal muscle, which needs nervous stimulation to contract. The heart's rhythmic contractions occur spontaneously, although the frequency of the contractions, called the **heart**

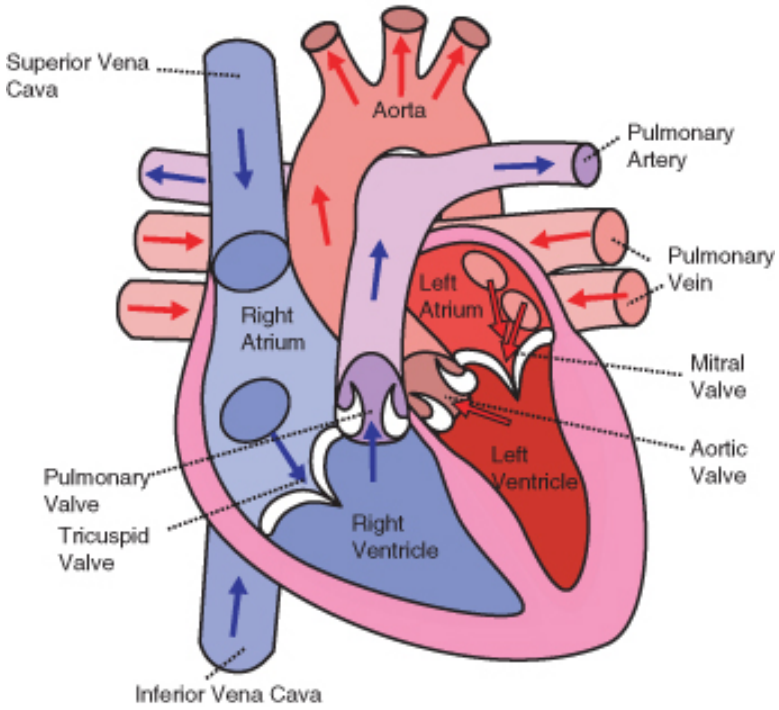


Figure 22.4: The direction of blood flow through the heart.

rate, can be changed by nervous or hormonal signals such as exercise or the perception of danger.

Control of the Heartbeat

The rhythmic sequence of contractions of the heart is coordinated by two small groups of cardiac muscle cells called the sinoatrial (SA) and atrioventricular (AV) nodes. The **sinoatrial node (SA node)**, often known as the "cardiac pacemaker", is found in the upper wall of the right atrium and is responsible for the wave of electrical stimulation that starts atrial contraction by creating an action potential. The action potential causes the cardiac cells to contract. This wave of contraction then spreads across the cells of the atrium, reaching the **atrioventricular node (AV node)** which is found in the lower right atrium, shown in **Figure** 22.5. The AV node conducts the electrical impulses that come from the SA node through the atria to the ventricles. The impulse is delayed there before being conducted through special bundles of heart muscle cells called the bundle of His and the Purkinje fibers, which leads to a contraction of the ventricles. This delay allows for the ventricles to fill with blood before the ventricles contract. Heartbeat is also controlled by nerve messages originating from the autonomic nervous system.

There are important physiological differences between cardiac cells found in the nodes and

cardiac cells found in the ventricles. Differences in ion channels and mechanisms of polarization give rise to unique properties of SA node cells, most importantly the spontaneous depolarizations necessary for the SA node's pacemaker activity.

The **Bundle of His** is a collection of heart muscle cells (fibers) specialized for electrical conduction that transmits the electrical impulses from the AV node. The bundle of His branches into Purkinje fibers. **Purkinje fibers**, shown in **Figure** 22.6, are specialized cardiac muscle cells that conduct action potentials into the ventricles, causing the cardiac muscle of the ventricles to contract in a controlled way.

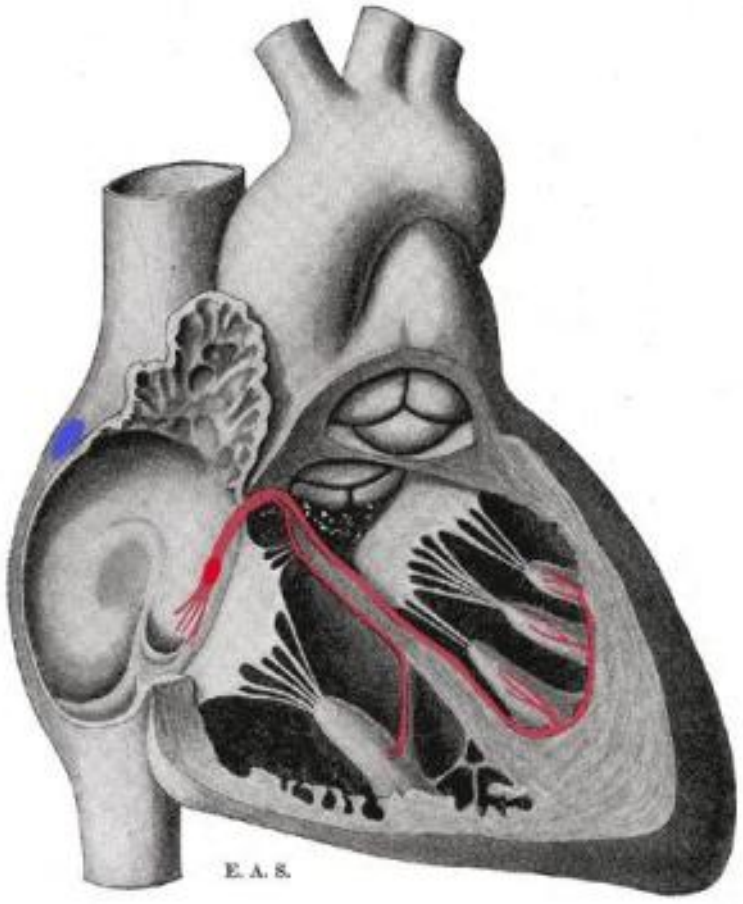


Figure 22.5: Schematic representation of the atrioventricular Bundle of His. The SA node is blue, and the AV node is red and visible in the right atrium. The AV node forms the Bundle of His. Sometimes the left and right Bundles of His are called Purkinje fibers.

The heartbeat is made up of two parts; muscle contraction and relaxation. **Systole** is the contraction of the heart chambers, which drives blood out of the chambers. **Diastole** is the period of time when the heart relaxes after contraction. All four chambers of the heart undergo systole and diastole in a timed fashion so that blood is moved forward through the

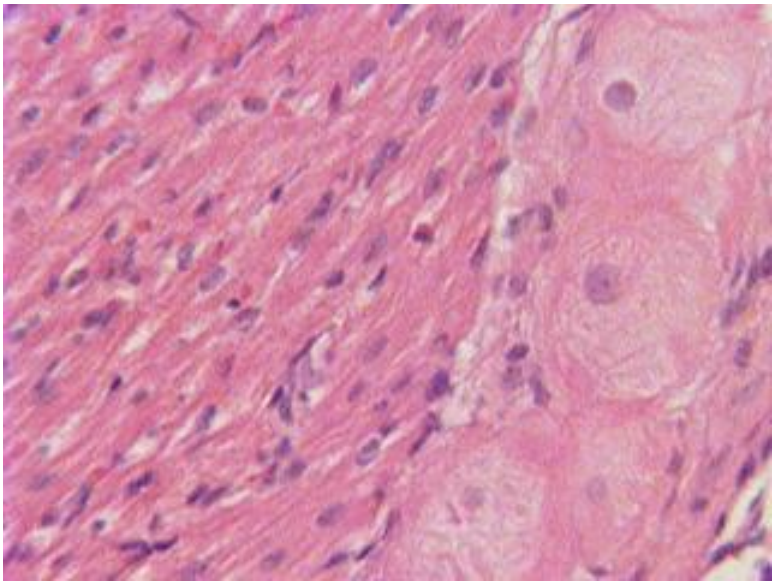


Figure 22.6: The larger round cells on the right are Purkinje fibers. Because of their specializations to rapidly conduct impulses (numerous sodium ion channels and mitochondria, fewer myofibrils than the surrounding muscle tissue), Purkinje fibers take up stain differently than the surrounding muscles cells, and on a slide, they often appear lighter and larger than their neighbors.

cardiovascular system. For example, ventricular systole is the point at which the ventricles are contracting, and atrial systole is the point at which the atria are contracting. Likewise, ventricular diastole is the period during which the ventricles are relaxing, while atrial diastole is the period during which the atria are relaxing. In general, when referring to systole and diastole, the chambers being referred to are the ventricles, which is shown in **Figure** 22.7.

Heart Sounds

In healthy adults, there are two normal heart sounds often described as a ”lub” and a ”dub” that occur with each heart beat (lub-dub, lub-dub). In addition to these normal sounds, a variety of other sounds may be heard including heart murmurs or clicks. A medical practitioner uses a stethoscope to listen for these sounds, which gives him or her important information about the condition of the heart.

The sound of the heart valves shutting causes the heart sounds, or a heartbeat. The closing of the mitral and tricuspid valves (known together as the atrioventricular valves) at the beginning of ventricular systole cause the first part of the ”lub-dub” sound made by the heart as it beats. The second part of the ”lub-dub” is caused by the closure of the aortic and pulmonic valves at the end of ventricular systole. As the left ventricle empties, its pressure falls below the pressure in the aorta, and the aortic valve closes. Similarly, as the pressure

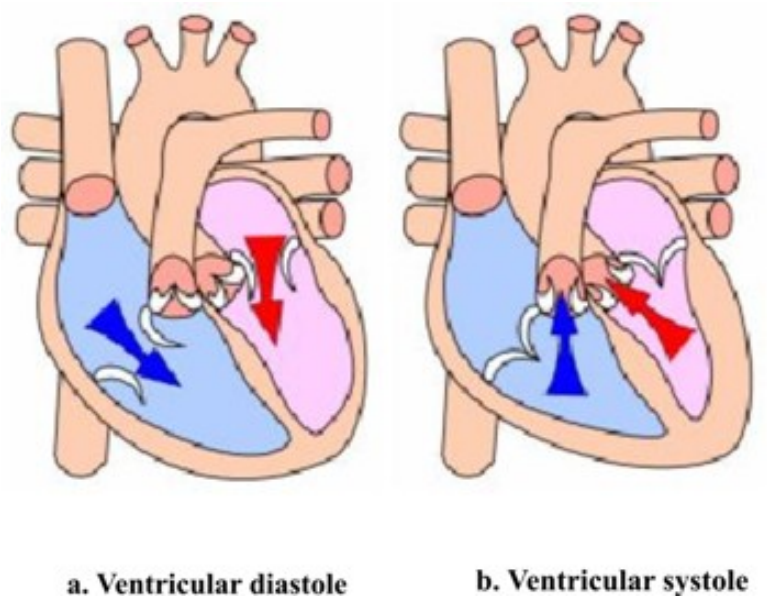


Figure 22.7: When the atria contract, the blood gets pushed into the ventricles which are in diastole. When the ventricles contract (ventricular systole), the blood gets pushed out of the heart.

in the right ventricle falls below the pressure in the pulmonary artery, the pulmonic valve closes.

Blood Vessels

The blood vessels are part of the cardiovascular system and function to transport blood throughout the body. The two most important types are arteries and veins. Arteries carry blood away from the heart, while veins return blood to the heart.

There are various kinds of blood vessels, the main types are:

- **Arteries** are the large, muscular vessels that carry blood away from the heart.
- An **arteriole** is a small diameter blood vessel that extends and branches out from an artery and leads to capillaries.
- **Veins** are vessels that carry blood toward the heart. The majority of veins in the body carry low-oxygen blood from the tissues back to the heart.
- A **venule** is a small vessel that allows deoxygenated blood to return from the capillaries to veins.
- **Capillaries** are the smallest of the body's blood vessels, that connect arterioles and venules, and are important for the interchange of gases and other substances between blood and body cells.

The blood vessels have a similar basic structure. The **endothelium** is a thin layer of cells that creates a smooth lining on the inside surface of blood vessels. Endothelial tissue is a specialized type of epithelium, one of the four types of tissue found in the body. Endothelial cells have an important structural role in blood vessels; they line the entire circulatory system, from the heart to the smallest capillary. Around the endothelium there is a layer of smooth muscle, which is well developed in arteries. Finally, there is a further layer of connective tissue that surrounds the smooth muscle. This connective tissue, which is mostly made up of collagen, contains nerves that supply the smooth muscular layer. The connective tissue surrounding larger vessels also contains capillaries to bring nutrients to the tissue. Capillaries, the smallest blood vessels, are made up of a single layer of endothelium and a small amount of connective tissue.

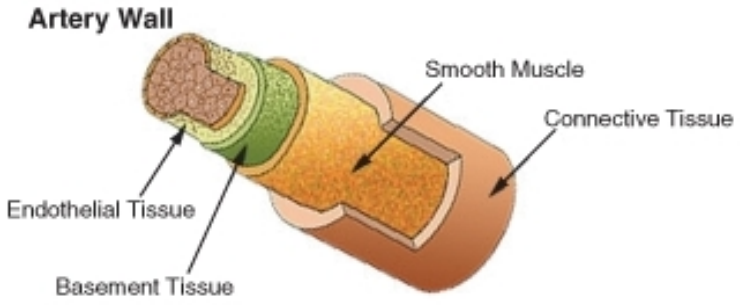


Figure 22.8: The structure of an artery wall.

Arteries and Arterioles

The arteries carry blood away from the heart. As shown in **Figure** 22.8, arteries have thick walls that have three major layers; an inner endothelial layer, a middle layer of smooth muscle, and an outer layer of stretchy connective tissue (mostly collagen). The elastic qualities of artery walls allow them to carry pressurized blood from the heart while maintaining blood pressure.

The aorta is the largest artery in the body. It receives blood directly from the left ventricle of the heart through the aortic valve. The aorta branches, into smaller arteries and these arteries branch in turn, becoming smaller in diameter, down to arterioles. The arterioles supply the capillaries that carry nutrients to the body's cells and tissues. The aorta is an elastic artery. When the left ventricle contracts to force blood into the aorta, it expands. This stretching gives the potential energy that will help maintain blood pressure during diastole when the aorta contracts passively.

An arteriole is a small-diameter blood vessel that branches out from an artery and leads to capillaries. Arterioles have thin muscular walls, composed of one or two layers of smooth muscle, and are the primary site of vascular resistance. **Vascular resistance** is the resistance

to flow that blood must overcome to be pumped through your circulatory system. Increasing vascular resistance is one way your body can increase blood pressure.

Veins and Venuoles

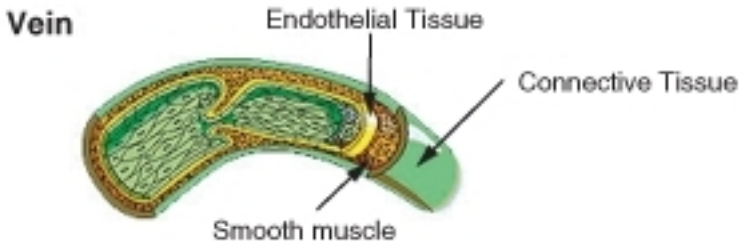


Figure 22.9: Internal structure of a vein.

Veins return deoxygenated blood to the heart. The thick, outer layer of a vein is made up of collagen-containing connective tissue, shown in **Figure** 22.9. The connective tissue is wrapped around bands of smooth muscle while the interior is lined with endothelium. Most veins have one-way flaps called valves, shown in in **Figure** 22.10, that prevent blood from flowing backward and pooling in the legs, feet, arms or hands due to the pull of gravity. The location of veins can vary from person to person.

A venule is a small blood vessel that allows deoxygenated blood to return from the capillary beds to the larger blood vessels called veins. Venules have three layers: an inner endothelium composed of squamous epithelial cells that act as a membrane, a middle layer of muscle and elastic tissue, and an outer layer of fibrous connective tissue. The middle layer is poorly developed so that venules have thinner walls than arterioles.

Capillaries

Capillaries are the smallest of a body's blood vessels, measuring 5-10 m in diameter. Their size is shown in relation to body cells in **Figure** 22.11. Capillaries connect arterioles and venules, and they are important for the exchange of oxygen, carbon dioxide, and other substances between blood and body cells.

The walls of capillaries are made of only a single layer of endothelial cells. This layer is so thin that molecules such as oxygen, water and lipids can pass through them by diffusion and enter the body tissues. Waste products such as carbon dioxide and urea can diffuse back into the blood to be carried away for removal from the body. Capillaries are so small the blood cells need to pass through it in a single file line. A capillary bed is the network of capillaries supplying an organ. The more metabolically active a tissue or organ is, the more capillaries it needs to get nutrients and oxygen.

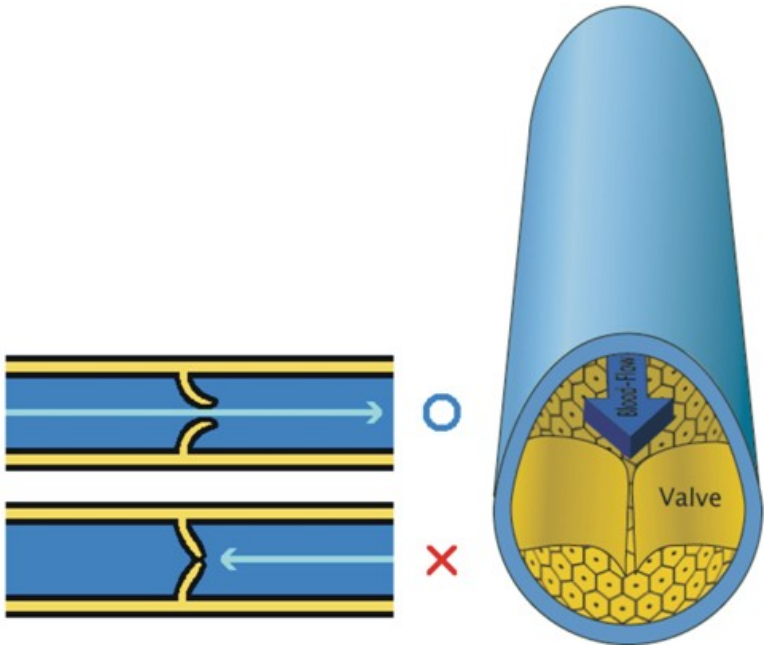


Figure 22.10: Valves found in veins prevent the blood from flowing backward and pooling in the lowest parts of the body, such as the legs and feet.

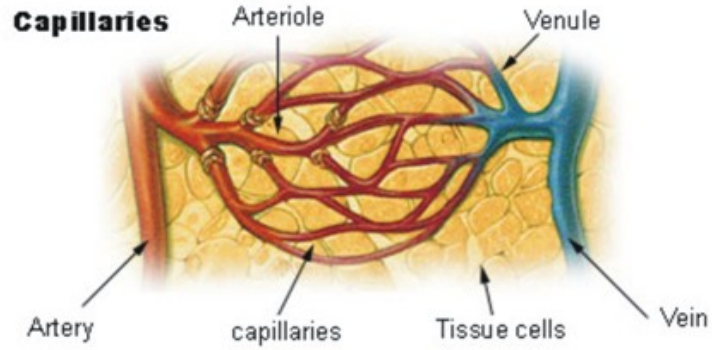


Figure 22.11: The structure of capillaries. Note their size in comparison to the cells around them.

Blood vessels are roughly grouped as arterial and venous. This grouping is determined by whether the blood in the vessel is flowing away from (arterial) or toward (venous) the heart. In general the term arterial blood is used to describe blood high in oxygen, although the pulmonary arteries carry deoxygenated blood and blood flowing in the pulmonary vein is rich in oxygen.

Roles of Blood Vessels

Blood vessels are not involved in regulating the transport of blood, the endocrine and nervous systems do that. However, arteries and veins can regulate their inner diameter by contraction of the smooth muscle layer. This widening or narrowing of the blood vessels changes the blood flow to the organs of the body. This process is controlled by the autonomic nervous system; it is not controlled consciously.

Vasodilation is a process by which blood vessels in the body become wider due to the relaxation of the smooth muscle in the vessel wall. This reduces blood pressure since there is more room for the blood to move through the vessel. Endothelium of blood vessels uses nitric oxide to signal the surrounding smooth muscle to relax, which dilates the artery and increasing blood flow. Nitric dioxide is a vasodilator.

Vasoconstriction is the constriction of blood vessels (narrowing, becoming smaller in cross-sectional area) by contracting the vascular smooth muscle in the vessel walls. Vasoconstriction is controlled by substances such as some hormones and neurotransmitters, which are called vasoconstrictors. For example, the "fight or flight" hormone epinephrine is a vasoconstrictor that is released by the adrenal glands.

Permeability of the endothelium is important for the release of nutrients to the tissue. Permeability is the ability of a membrane to allow certain molecules and ions to pass through it by diffusion. Permeability of the endothelium increases during an immune response, which allows white blood cells and other substances to get to the site of injury or irritation.

Oxygen, which is bound to hemoglobin in red blood cells for transport through the body, is the most critical nutrient carried by the blood. In all arteries apart from the pulmonary artery, hemoglobin is highly saturated (95-100%) with oxygen. In all veins apart from the pulmonary vein, the hemoglobin is desaturated at about 70%. (The values are reversed in the pulmonary circulation.)

Blood Vessels and Blood Pressure

Blood pressure refers to the force exerted by circulating blood on the walls of blood vessels. The pressure of the circulating blood gradually decreases as blood moves from the arteries, arterioles, capillaries, and veins. The term "blood pressure" generally refers to **arterial pressure**, which is the pressure in the larger arteries that take blood away from the heart.

Arterial pressure results from the force that is applied to blood by the contracting heart, where the blood "presses" against the walls of the arteries.

The systolic arterial pressure is defined as the peak pressure in the arteries, which occurs near the beginning of the cardiac cycle; the diastolic arterial pressure is the lowest pressure (at the resting phase of the cardiac cycle).

Arterial pressure is most commonly measured by a **sphygmomanometer**, shown in **Figure** 22.12. The height of a column of mercury indicates the pressure of the circulating blood. Although many modern blood pressure devices no longer use mercury, values are still universally reported in millimeters of mercury (mmHg).

Figure 22.12: The new and the "classic" ways to measure blood pressure. A digital sphygmomanometer, shown on the left, runs on electricity or batteries and measure blood pressure automatically. The cuff, which you can see behind the digital readout, is wrapped around the upper arm, just like the cuff of the older devices. The cuff then inflates automatically and measures blood pressure as the cuff deflates. The older, mechanical sphygmomanometer with a cuff and pressure reader and stethoscope is shown at right. The cuff is inflated and deflated manually while a medical technician listens for related changes in the sound of blood moving through arteries in the arm.

Blood Pressure Ranges

In the U.S., the healthy ranges for arterial pressure are:

- Systolic: less than 120 mm Hg
- Diastolic: less than 80 mm Hg

Blood pressure is usually written as systolic/diastolic mm Hg; for example, a reading of 120/80 mm Hg, is said as "one twenty over eighty." These measures of arterial pressure are not static, but go through natural variations from one heartbeat to another and throughout the day (in a circadian rhythm). Factors such as age, gender and race influence blood pressure values. Pressure also varies with exercise, emotional reactions, sleep, stress, nutritional factors, drugs, or disease.

Studies have shown that people whose systolic pressure is around 115 mm Hg rather than 120 mmHg have fewer health problems. Clinical trials have shown that people who have arterial pressures at the low end of these ranges have much better long term cardiovascular health for this reason some researchers say that 115/75 mm Hg should be the ideal measurement.

Hypertension is a condition in which a person's blood pressure is chronically high. Hypertension is said to be present when a person's systolic blood pressure is always 140 mm Hg or higher, and/or their diastolic blood pressure is always 90 mm Hg or higher. Blood pressure readings between 120/80 mmHg and 139/89 mmHg are called prehypertension. Prehypertension is not a disease category; rather, it is a way to identify people who are at high risk of developing hypertension.

Arterioles and Blood Pressure

Arterioles have the greatest collective influence on both local blood flow and on overall blood pressure. They are the primary "adjustable nozzles" in the blood system, across which the greatest pressure drop occurs. The combination of heart output (cardiac output) and systemic vascular resistance, which refers to the collective resistance of all of the body's arterioles, are the principal determinants of arterial blood pressure at any given moment.

Pulmonary and Systemic Circulations

The double circulatory system of blood flow refers to the separate systems of pulmonary circulation and the systemic circulation in amphibians, birds and mammals, including humans. The adult human heart consists of two separated pumps, the right side which pumps deoxygenated blood into the pulmonary circulation, and the left side which pumps oxygenated blood into the systemic circulation. Blood in one circuit has to go through the heart to enter the other circuit, as shown in **Figure** 22.13.

Pulmonary Circulation

The **pulmonary circulation** is the portion of the cardiovascular system which carries oxygen-poor (deoxygenated) blood away from the heart, to the lungs, and returns oxygenated blood back to the heart. As shown in **Figure** 22.14, deoxygenated blood from the body leaves the right ventricle through the pulmonary arteries, which carry the blood to each lung. The pulmonary arteries are the only arteries that carry deoxygenated blood. In the lungs, red blood cells release carbon dioxide and pick up oxygen during respiration. The oxygenated blood then leaves the lungs through the pulmonary veins, which return it to the left side of the heart, and complete the pulmonary cycle. The oxygenated blood is then distributed to the body through the systemic circulation before returning again to the pulmonary circulation.

The pulmonary circulation was first discovered by a Syrian physician, Ibn al-Nafis, in 1242.

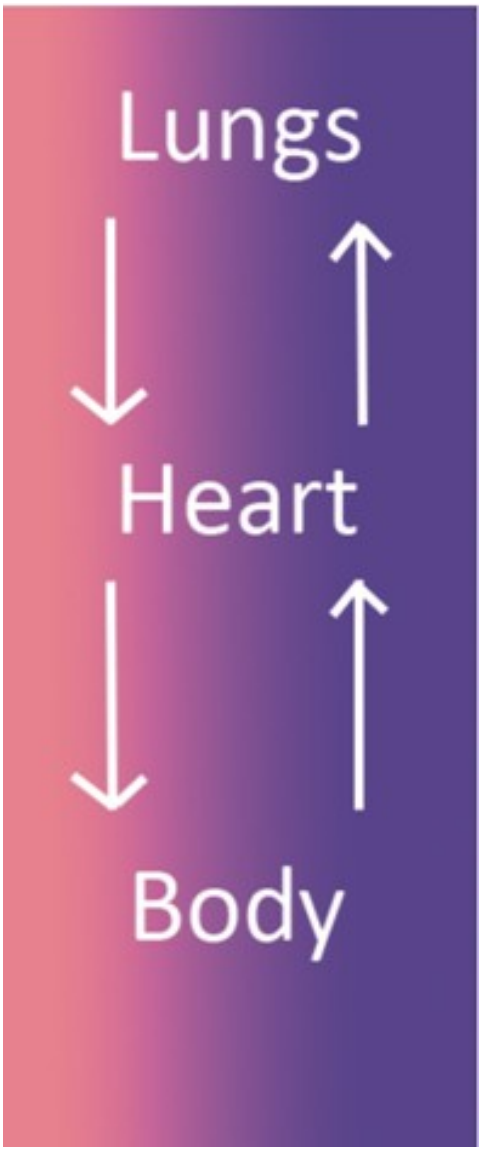


Figure 22.13: The double circulatory system. Blood in one circuit has to go through the heart to enter the other circuit. The heart-to-lungs-to heart portion is the pulmonary circulation, and the heart-to-body-to-heart portion is the systemic circulation.

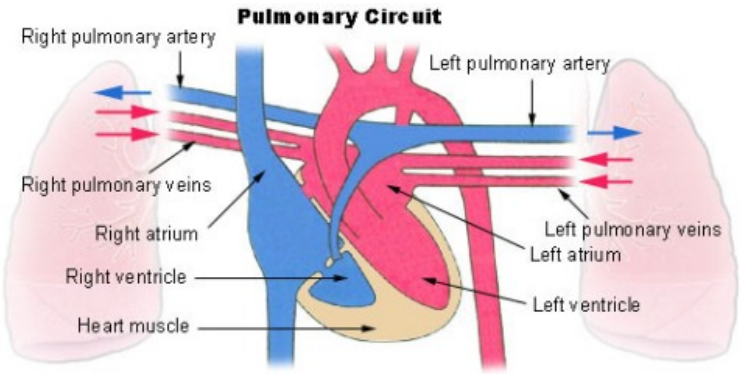


Figure 22.14: Pulmonary circulation. The pulmonary arteries carry oxygen-poor blood from the right ventricle to the lungs, and the pulmonary veins return oxygenated blood to the left side of the heart. This "loop" is called the pulmonary cycle.

However, credit for the first description of blood circulation is given to an English medical doctor William Harvey, who in 1616 described in detail the pulmonary and systemic circulation systems.

Systemic Circulation

The **systemic circulation** is the portion of the cardiovascular system which carries oxygenated blood away from the heart, to the body, and returns deoxygenated blood back to the heart. Oxygenated blood from the lungs leaves the left ventricle through the aorta, from where it is distributed to the body's organs and tissues, which absorb the oxygen, through a complex network of arteries, arterioles, and capillaries. The deoxygenated blood is then collected by venules, from where it flows first into veins, and then into the inferior and superior venae cavae, which return it to the right heart, completing the systemic cycle, shown in **Figure** 22.15. The blood is then re-oxygenated through the pulmonary circulation before returning again to the systemic circulation.

Just like every other organ in the body, the heart needs its own blood supply, which it gets through the **coronary circulation**. Although blood fills the chambers of the heart, the heart muscle tissue is so thick that it needs blood vessels to deliver oxygen and nutrients deep within it. The vessels that deliver oxygen-rich blood to the heart muscle are called coronary arteries, they branch directly from the aorta, just above the heart, shown in **Figure** 22.16. The vessels that remove the deoxygenated blood from the heart muscle are known as cardiac veins.

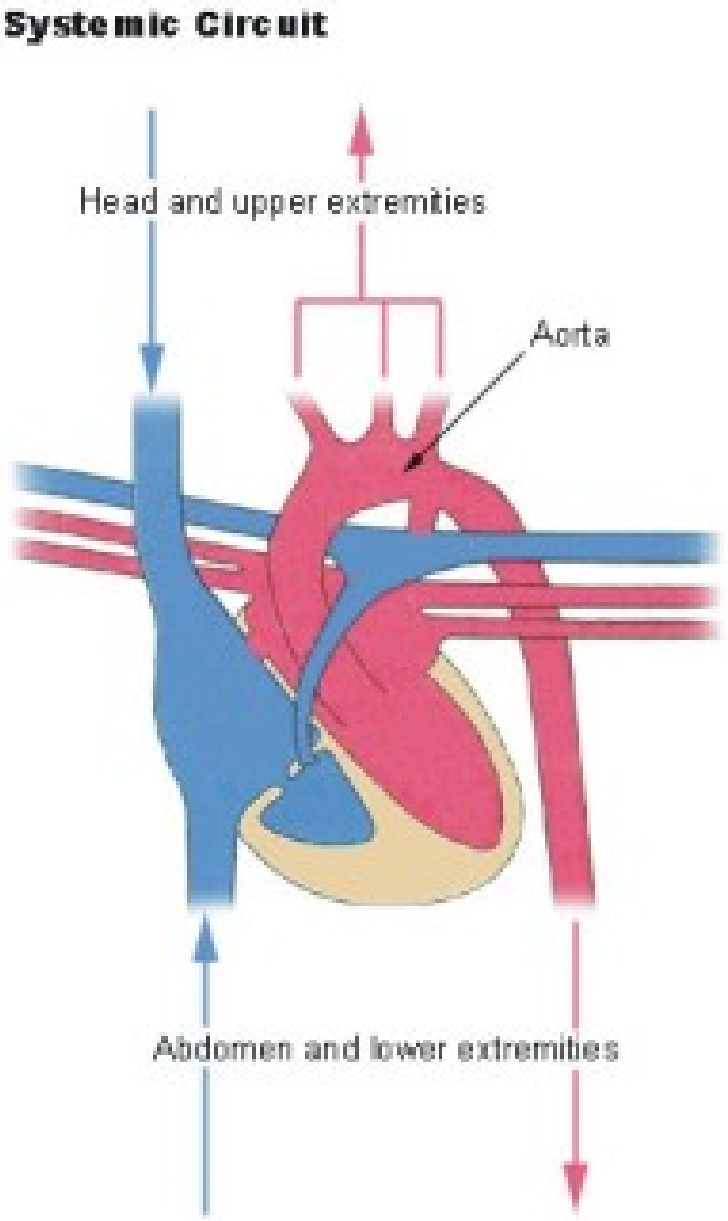


Figure 22.15: The systemic circulation. The systemic circulation brings oxygenated blood to the body cells and tissues and transports cellular wastes. It is also responsible for temperature regulation and transport of hormones and other substances around the body.

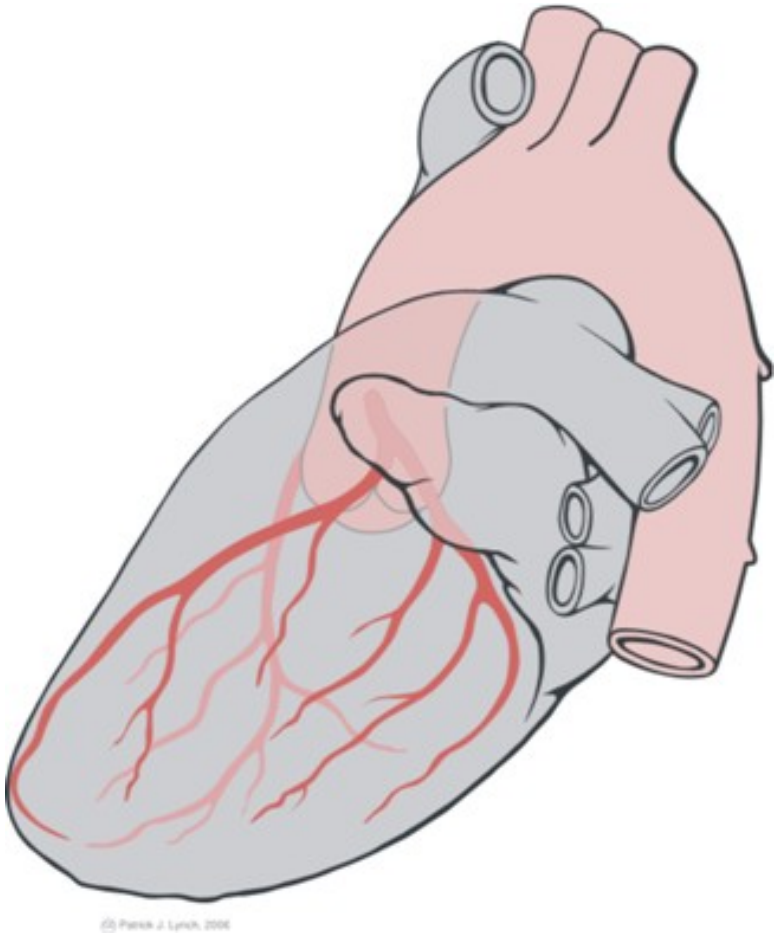


Figure 22.16: This side view (lateral view), of the heart shows how the coronary arteries (in red) branch directly from the aorta to bring oxygen and nutrients into the heart muscle.

Portal Venous System

A **portal venous system** occurs when a capillary bed drains into another capillary bed through veins. They are relatively uncommon as the majority of capillary beds drain into the heart, not into another capillary bed. Portal venous systems are considered venous because the blood vessels that join the two capillary beds are either veins or venules.

An example of a portal venous system is the blood vessel network between the digestive tract and the liver. The hepatic portal system is responsible for directing blood from parts of the gastrointestinal tract to the liver. Nutrients that have been absorbed into the blood from the small intestine are taken to the liver for processing before being sent to the heart. The term, "portal venous system" often refers to the hepatic portal system.

Lymphatic System

The **lymphatic system**, shown in **Figure** 22.17, is a complex network of lymph nodes, lymph ducts, lymphatic tissues, lymph capillaries and lymph vessels that extend the length of the body. It serves as a conduit for a fluid called lymph. The lymphatic system is often called the secondary circulatory system.

The lymphatic system has three related functions:

- The removal of excess fluids from body tissues.
- The absorption of fats, also known as fatty acids or lipids, and transport of fats to the cardiovascular system.
- The production of certain types of white blood cells, which aid in the body's immune response.

Lymph originates as blood plasma that leaks from the capillaries of the cardiovascular system. This blood plasma fills the space between individual cells of tissue where it becomes part of the interstitial fluid. Plasma is forced out of the capillaries and forced back in due to interactions of hydrostatic pressure. While out of the blood capillaries, the plasma increases the volume of the interstitial fluid. Most of the interstitial fluid is returned to the capillaries by osmosis. The excess interstitial fluid is collected by the lymphatic system by diffusion into **lymph capillaries**, and is processed by lymph nodes before to being returned to the circulatory system. Once within the lymphatic system the fluid is called lymph, and has almost the same composition as the original interstitial fluid.

Fatty acids, also known as fats or lipids, are transported through the cardiovascular system differently than other nutrients, such as proteins and sugars. Lipids are absorbed by cells in the villi of the small intestine where they form a complex with protein molecules. These lipo-proteins are called **chylomicrons**. The chylomicrons are transported via the lymphatic system and eventually rejoin the bloodstream to be processed by the liver.

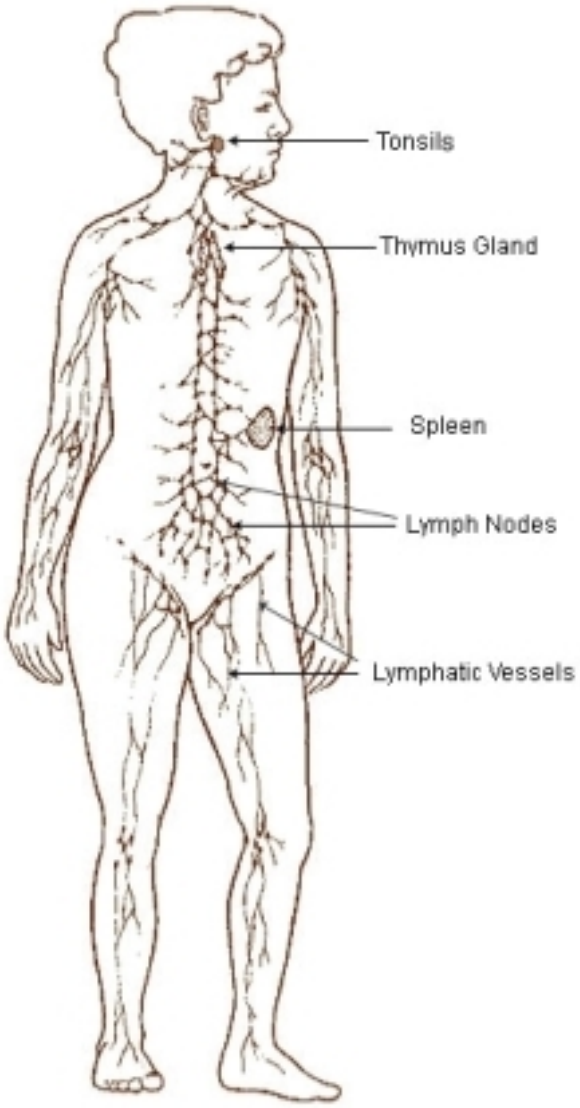


Figure 22.17: Lymphatic system

The lymphatic system is a major component of the immune system. The lymphatic system has many lymph nodes. **Lymph nodes** are filters or traps for foreign particles and contain white blood cells. Human lymph nodes are bean-shaped and range in size from a few millimeters to about 1 to 2 cm. White blood cells are located within honeycomb structures of the lymph nodes. Lymph that moves through the lymph nodes is filtered so that microorganisms and tissue debris are removed. Lymph nodes swell and feel sore when the body is infected due to the increased production of white blood cells.

The spleen and tonsils are large lymphoid organs that serve similar functions to lymph nodes, though the spleen filters blood cells rather than bacteria or viruses.

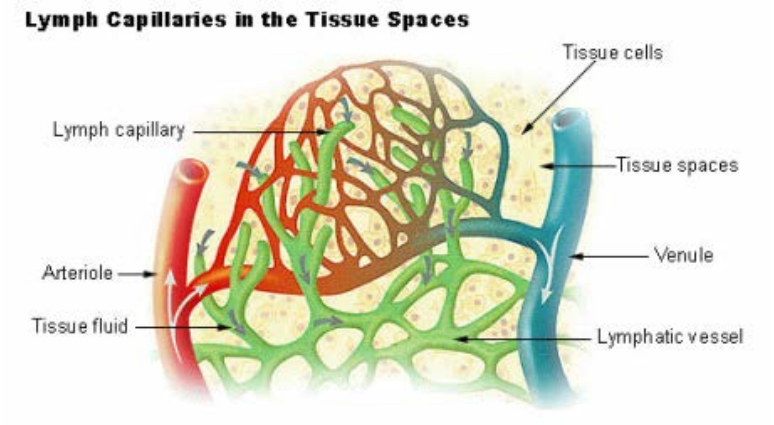


Figure 22.18: The movement of lymph from the interstitial fluid into the lymphatic vessels. Lymph moves in only one direction through the blood vessels.

Lymphatic Circulation

Unlike the blood system, the lymphatic system is not closed and has no central pump. Lymph movement occurs slowly with low pressure due to peristalsis, valves, and the squeezing action of skeletal muscles. Lymph travels through lymph vessels that are similar to capillaries and veins. Lymph moves in one direction only, due to valves in lymph vessels that are similar to the valves found in veins, shown in **Figure** 22.18. The movement of lymph depends on the movement of skeletal muscles to squeezing the lymph through them, especially near the joints. Rhythmic contraction of the vessel walls through movements may also help draw fluid into the small lymphatic capillaries. The lymph is then transported to progressively larger lymphatic vessels that drain into the circulatory system at the right and left subclavian veins.

Homeostatic Imbalance of the Lymphatic System

In the disease known as elephantiasis, shown in **Figure** 22.19, infection of the lymphatic vessels cause a thickening of the skin and enlargement of the underlying tissues, especially in the legs and genitals. It is most commonly caused by infection by parasitic roundworms.

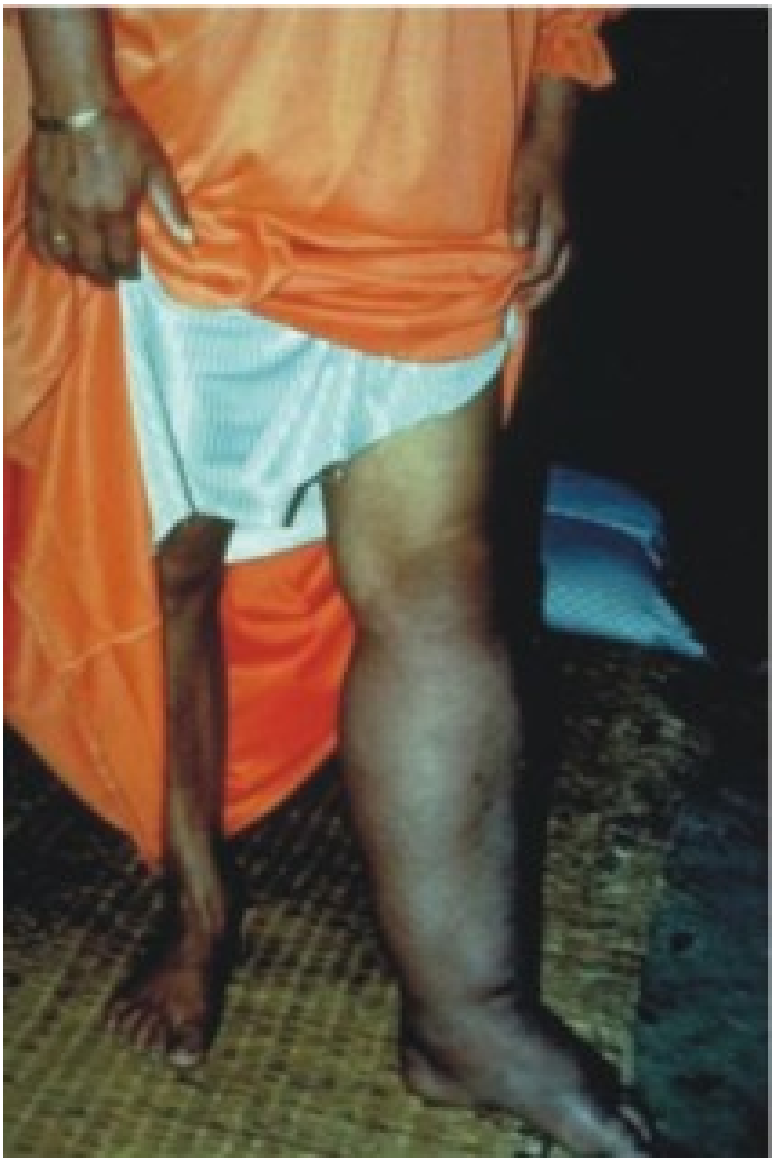


Figure 22.19: Over a billion people are at risk for infection by filarial nematodes, the parasites that cause elephantiasis.

Lymphedema also causes abnormal swelling, especially in the arms and legs (though the face, neck, and abdomen can also be affected). It occurs if the lymphatic system is damaged, or underdeveloped in some way. An estimated 170 million suffer with the disorder.

Lymphoma, or lymphatic cancer, is cancer of the lymphatic system. According to the American Cancer Society, in 2007, lymphoma accounted for 4 percent of new cancer cases amongst men and women in the United States. In lymphoma, cells of the lymphatic system grow abnormally. They divide too rapidly and grow without any order or control. Because lymphatic tissue is present in many parts of the body, lymphoma can start almost anywhere. Lymphoma may occur in a single lymph node, a group of lymph nodes, or, sometimes, in other parts of the lymphatic system such as the bone marrow and spleen.

Homeostatic Imbalances of the Cardiovascular System

Cardiovascular disease (CVD) refers to any disease that affects the cardiovascular system, but it is usually used to refer to diseases related to **atherosclerosis**, which is a chronic inflammatory response in the walls of arteries that causes a swelling and buildup of materials called **plaque**. Plaque is made of cell debris, cholesterol, fatty acids, calcium, and fibrous connective tissue that build up around an area of inflammation. As a plaque grows it stiffens and narrows the artery, which reduces the flow of blood through the artery, shown in **Figure** 22.20.

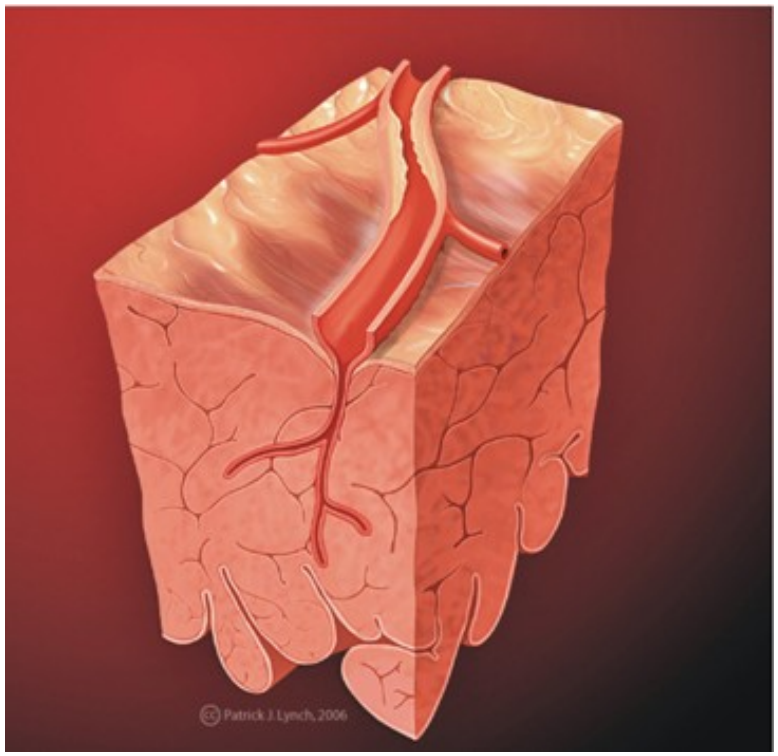


Figure 22.20: Atherosclerosis is sometimes referred to as hardening of the arteries.

Atherosclerosis

Atherosclerosis normally begins in later childhood, and is usually found in most major arteries. It does not usually have any early symptoms. Causes of atherosclerosis include a high-fat diet, high cholesterol, smoking, obesity, and diabetes. Atherosclerosis becomes a threat to health when the plaque buildup interferes with the blood circulation in the heart (coronary circulation) or the brain (cerebral circulation). A blockage in the coronary circulation, can lead to a heart attack, and blockage of the cerebral circulation (leading to, or within the brain) can lead to a stroke. According to the American Heart Association, atherosclerosis is a leading cause of CVD.

Coronary Heart Disease

Cardiac muscle cells are fed by the coronary arteries. Blocked flow in a coronary artery can result in oxygen starvation and death of heart muscle. **Coronary heart disease** is the end result of the buildup of plaques within the walls of the coronary arteries, shown in **Figure** 22.21. Most individuals with coronary heart disease have no symptoms for many years until the first sign, often a heart attack, happens.

A symptom of coronary heart disease is chest pain. Occasional chest pain, called angina pectoralis (or angina) can happen during times of stress or physical exertion. The pain of angina means the heart muscle fibers need more oxygen than they are getting.

A **heart attack**, also called a **myocardial infarction (MI)**, occurs when the blood supply to a part of the heart is blocked, as shown in **Figure** 22.22. A heart attack can occur from the buildup and blockage of a coronary artery by plaque, or it can be caused by a small piece of plaque that breaks away when a larger plaque breaks apart. This piece of free-floating plaque, called an embolus, can get stuck in a coronary blood vessel, causing a blockage or **embolism**. Cardiac muscle fibers that are starved of oxygen for more than five minutes will die, and because they do not divide, dead cardiac muscle cells cannot be replaced. Coronary heart disease is the leading causes of death of adults in the United States. For an animation depicting a heart attack, see http://www.byrnehealthcare.com/animations/SutterHeartAttack.htm.

Stroke

Since atherosclerosis is a body wide process, similar events can also occur in the arteries to other parts of the body, including the brain. A **stroke** is a loss of brain function due to a stoppage of the blood supply to the brain. It can be caused by a blot clot (thrombosis), a free-floating object that gets caught in a blood vessel (embolism), or by bleeding (hemorrhage). For an animation depicting a stroke, see http://www.byrnehealthcare.com/animations/SutterStroke.htm.

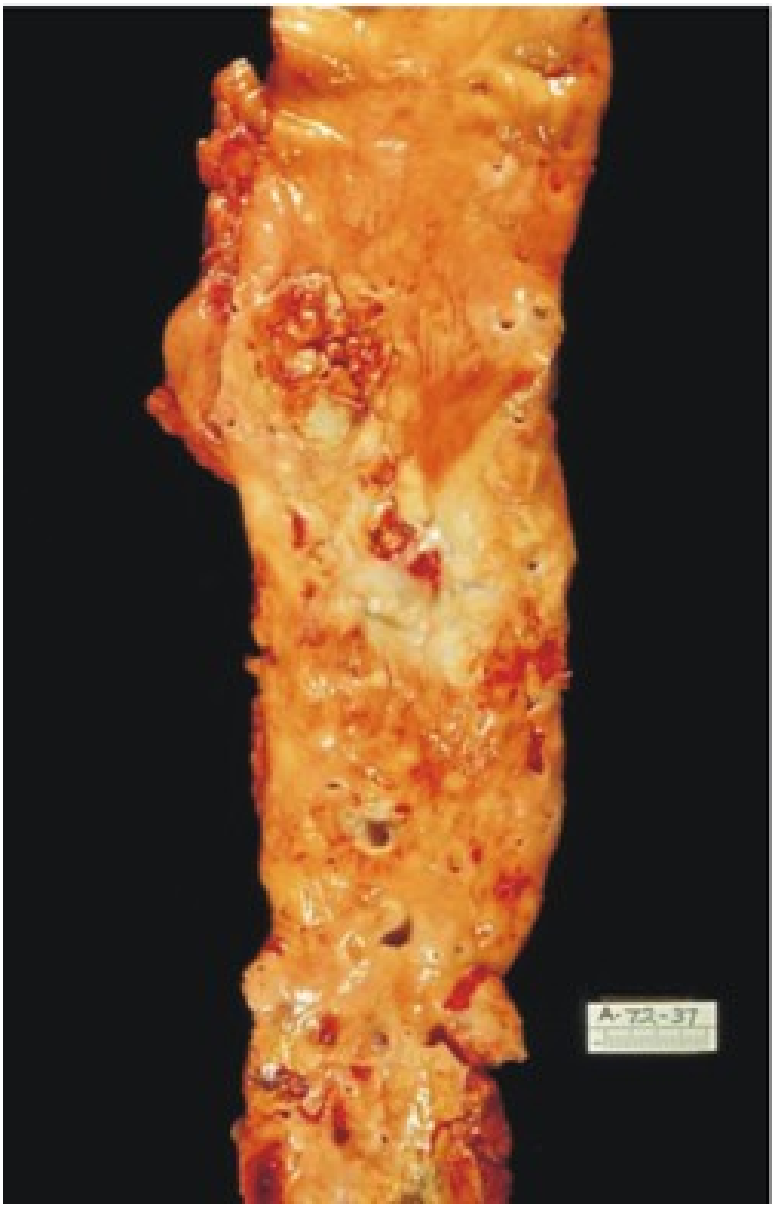
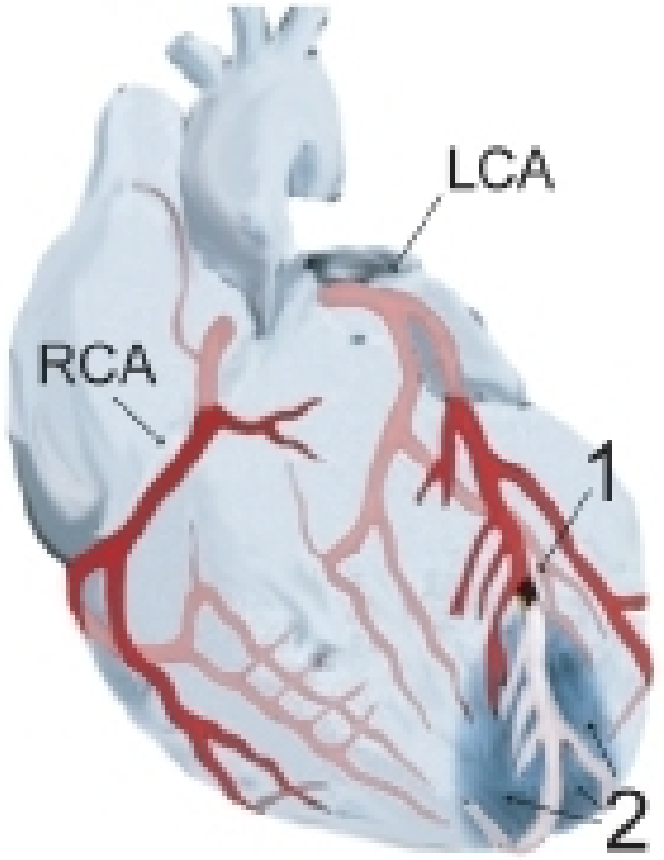


Figure 22.21: Autopsy specimen of an artery has been opened lengthwise to show the inside (lumen) which is completely blocked by many plaques. For a video depicting atherosclerosis, see . For an atherosclerosis animation, see



LCA-Left Coronary Artery
RCA-Right Coronary Artery
1-Blockage
2-Blood supply stopped to lower part of heart.

Figure 22.22: Diagram of a heart attack (myocardial infarction). The blood supply to the lower part of the heart is stopped after a blockage of the lower portion of the left coronary artery (LCA). For an animation depicting coronary artery disease, see

Risk factors for stroke include advanced age, high blood pressure, previous stroke, diabetes, high cholesterol, and cigarette smoking. Reduction of blood pressure is the most important modifiable risk factor of stroke; however many other risk factors, such as quitting tobacco smoking, are also important.

Preventing Cardiovascular Diseases

There are many risk factors which are associated with various forms of cardiovascular disease, some of these you cannot control, but many you can control.

Non-controllable risk factors include:

- Age: The older a person is, the greater their chance of developing a cardiovascular disease.
- Gender: Men under age 64 are much more likely to die of coronary heart disease than women, although the gender difference declines with age.
- Genetics: Family history of cardiovascular disease affects a person's chance of developing heart disease.

Controllable risk factors include:

- Tobacco Smoking: Giving up smoking is the single most effective way of reducing risk of heart disease.
- Diabetes: Having diabetes can cause metabolic changes (such as high cholesterol levels) which in themselves are risk factors.
- High cholesterol levels: High amounts of low density lipids (LDLs) in the blood, also called "bad cholesterol", are a significant risk factor.
- Obesity: Being obese, especially if the fat is deposited mostly in the torso, rather than the hips and thighs, increases risk significantly.
- High blood pressure: Hypertension can cause atherosclerosis.
- Lack of physical activity: Aerobic activities, including walking and vacuuming, that are done for 60 minutes a day, five days a week, help keep the heart healthy.
- Poor eating habits: Eating mostly foods that are nutrient poor (do not have many nutrients other than fat or carbohydrate) leads to high cholesterol levels and weight gain, among other things.

Although there are uncontrollable risk factors involved in CVD, a person whose family has a history of CVD is not destined to develop heart disease. There are many things such a person can do to help prevent CVD, even when predisposed to a disease. A person who is physically active every day, eats healthfully, and avoids tobacco can lower their chances of developing the disease.

Although men have a higher rate of cardiovascular disease than women, it is also the number one health problem for women in industrialized countries. After menopause, the risk for women is almost equal to that of men.

Cardiovascular Disease Awareness

Cardiovascular diseases are called "lifestyle diseases" because they are caused mostly by everyday choices that people make, such as what to eat for dinner, or what to do during their free time. For example, watching TV with your dog does not involve much moving around so it does not exercise the body, whereas bringing the dog for a walk outside exercises both of you. Decisions that you make today and everyday will affect your cardiovascular health many years from now, such as those shown in **Figure** 22.23.

Many studies have shown that plaque buildup starts in early adolescence. However, teens are more concerned about risks such as HIV, accidents, and cancer than cardiovascular disease. One in three people will die from complications due to atherosclerosis. For this reason there is an emphasis on the prevention of CVD through risk reduction. For example, healthy eating, regular physical activity, and avoidance of smoking can greatly decrease a person's chance of developing a CVD.

Figure 22.23: Limiting sedentary activities such as watching TV, and making more time for walking, hiking, cycling, or running will help develop a healthy heart.

Congenital Heart Defects

A **congenital heart defect** is a problem with the structure of the heart that is present at birth. Such heart defects are the most common type of major birth defect. Most heart defects either obstruct blood flow in the heart or vessels near it, or cause blood to flow through the heart in an abnormal pattern, although other defects affecting heart rhythm can also occur.

Treatment for a defect can include medicines, surgery, and other medical procedures and

heart transplants. The treatment depends on the type and severity of the defect and the child's age, size and general health. Also, certain mild defects that some children are born with are repaired over time by the body.

Lesson Summary

- The main components of the cardiovascular system are the heart, the blood vessels, and the blood. It moves nutrients, hormones, gases and wastes to and from body cells, and distributes heat to maintain homeostasis.
- Deoxygenated blood enters the right atrium from the body through the vena cava; oxygenated blood coming from the lungs through the pulmonary vein enters the left atrium. The atria then contract, pushing the blood into the ventricles. After a short delay, the ventricles contract, the oxygenated blood gets pushed through the aorta to the rest of the body, and the deoxygenated blood gets pushed to the lungs through the pulmonary arteries.
- Arteries have thick walls that have three major layers; an inner endothelial layer, a middle layer of smooth muscle, and an outer layer of stretchy connective tissue (mostly collagen). The thick, outer layer of a vein is made up of collagen-containing connective tissue. The connective tissue is wrapped around bands of smooth muscle while the interior is lined with endothelium. Most veins have one-way flaps called valves that prevent blood from flowing backward and pooling in the legs, feet, arms or hands due to the pull of gravity. The walls of capillaries are made of only a single layer of endothelial cells.
- The lymphatic system has three related functions; the removal of excess fluids from body tissues, the absorption of fats and transport of fat to the cardiovascular system, and the production of certain types of white blood cells.
- Atherosclerosis, which may lead to a heart attack, is a chronic inflammatory response in the walls of arteries that leads to a buildup of plaque. Plaque is made of cell debris, cholesterol, fatty acids, calcium, and fibrous connective tissue that build up around an area of inflammation. As a plaque grows it stiffens and narrows the artery, which reduces the flow of blood through the artery.
- Eating nutritious food, being physically active for 60 minutes on most days of the week, and avoiding smoking are three of the most effective things a person can do to avoid cardiovascular disease.

Summary Animation

- http://www.hostos.cuny.edu/oaa/heart/heart.html

Review Questions

1. Why is the left ventricle generally thicker than the right ventricle?
2. At what point do the pulmonary and systemic circulation systems meet up?
3. Why do veins have valves? Use the heart **Figure** 22.24 to answer the following four questions:

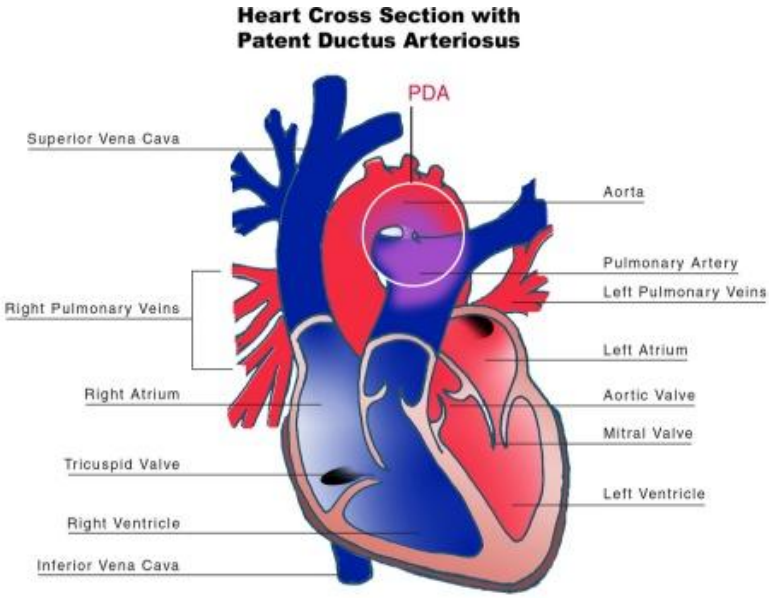


Figure 22.24

4. What two structures are involved in the patent ductus arteriosus shown in this diagram. (Hint: The patent ductus arteriosus is the structure found inside the white circle at top center).
5. Propose what might happen to blood flow around the site of the PDA.
6. Would a PDA be considered a heart defect? Explain your answer.
7. How might the PDA affect the body? Use **Figure** 22.25 of the estimated prevalence of cardiovascular disease (CVD) in the U.S. population to answer the following three questions.
8. What is the overall trend in the prevalence of CVD in the U.S. population?
9. In what age group does the prevalence of CVD in the female population equal that of the male population?
10. At what point does 50 percent of the male and female population have CVD?

Further Reading / Supplemental Links

- Vanhecke et al. Awareness, knowledge, and perception of heart disease among adolescents. EJCPR 2006;13:718-723.

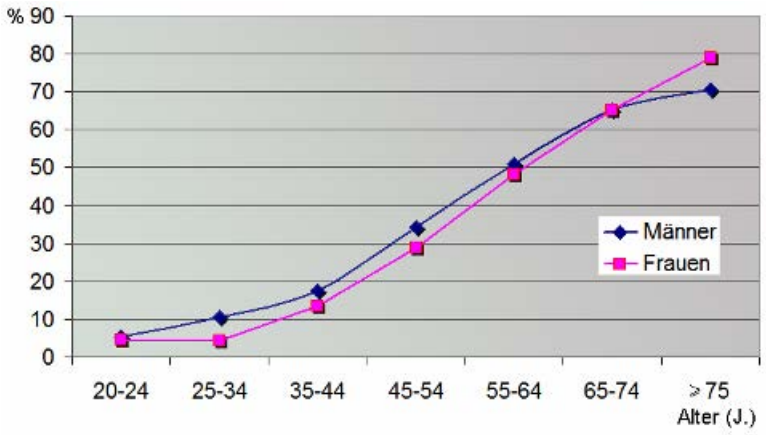


Figure 22.25

- Strong, J.P., et al. Prevalence and Extent of Atherosclerosis in Adolescents and Young Adults JAMA. 1999;281:727-735. Available online at:
- http://jama.ama-assn.org/cgi/content/full/281/8/727
- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookcircSYS.html
- http://training.seer.cancer.gov/ss_module08_lymph_leuk/lymph_unit01_sec01_intro.html
- http://www.nlm.nih.gov/medlineplus/ency/article/000171.htm#Causes,%20incidence,%20and%20risk%20factors
- http://www.nlm.nih.gov/medlineplus/congenitalheartdefects.html
- http://www.americanheart.org
- http://www.accessexcellence.org/
- http://whyfiles.org/090doping_sport/3.html
- http://whyfiles.org/
- http://en.wikipedia.org

Vocabulary

arteriole Small diameter blood vessel that extends and branches out from an artery and leads to capillaries.

artery Large, muscular vessels that carry blood away from the heart.

atria Thin-walled blood collection chambers of the heart, pump blood into the ventricles (singular, atrium).

atrioventricular node Conducts the electrical impulses that come from the SA node through the atria to the ventricles.

atrioventricular valves Ensure blood flows from the atria to the ventricles.

blood pressure The force exerted by circulating blood on the walls of blood vessels.

Bundle of His A collection of heart muscle cells (fibers) specialized for electrical conduction that transmits the electrical impulses from the AV node.

cardiovascular system An organ system that moves nutrients, hormones, gases and wastes to and from body cells, and distributes heat to maintain homeostasis.

capillary Smallest of the body's blood vessels, connects arterioles and venules, and are important for the interchange of gases and other substances between blood and body cells.

coronary circulation Supplies the heart tissue with blood.

diastole Period of time when the heart relaxes after contraction.

heart The muscular organ that pumps blood through the blood vessels by repeated, rhythmic contractions.

hypertension Condition in which a person's blood pressure is chronically high.

pulmonary circulation Portion of the cardiovascular system which carries deoxygenated blood away from the heart, to the lungs, and returns oxygenated blood back to the heart.

Purkinje fibers Specialized cardiac muscle cells that conduct action potentials into the ventricles, causing the cardiac muscle of the ventricles to contract in a controlled fashion.

semilunar valves Present in the arteries leaving the heart, prevent blood flowing back from the arteries into the ventricles.

sinoatrial node Known as the "cardiac pacemaker," found in the upper wall of the right atrium, is responsible for the wave of electrical stimulation that starts atrial contraction by creating an action potential.

sphygmomanometer Measures arterial pressure.

systemic circulation Portion of the cardiovascular system which carries oxygenated blood away from the heart, to the body, and returns deoxygenated blood back to the heart.

systole Contraction of the heart chambers, which drives blood out of the chambers.

vascular resistance Resistance to flow that blood must overcome to be pumped through your circulatory system.

vasoconstriction Constriction of blood vessels by contracting the vascular smooth muscle in the vessel walls.

vasodilatation Process by which blood vessels in the body become wider due to the relaxation of the smooth muscle in the vessel wall.

vein Vessel that carries blood toward the heart.

ventricles Heart chambers which collect blood from the atria and pump it out of the heart.

venule Small vessel that allows deoxygenated blood to return from the capillaries to veins.

Points to Consider

- How may factors such as the region of the world in which you live or your type of employment contribute to your risk of developing cardiovascular disease?
- Hypothesize about the role of blood in your excretory system.

22.2 Lesson 22.2: Blood

Lesson Objectives

- List three functions of blood.
- Describe the composition of blood.
- Outline the process of blood clotting.
- Identify two major blood group systems.
- Outline the significance of blood type in transfusions.
- Describe two diseases of the blood.

Introduction

Blood is a fluid connective tissue. It circulates around the body through the blood vessels by the pumping action of the heart. Arterial blood carries oxygen and nutrient to all the body's cells, and venous blood carries carbon dioxide and other metabolic wastes away from the cells.

In addition to the transport of gases, nutrients, and wastes, blood has many other functions that include:

- The removal of waste such as carbon dioxide, urea and lactic acid from the body tissues.
- The defense of the body against infection by microorganisms or parasites.
- The repair of damage to the body tissues.
- The transport of chemical messages, such as hormones and hormone-like substances.
- The control of body pH (the normal pH of blood is in the range of 7.35 - 7.45).
- The control of body temperature.

The Composition of Blood

Blood is a colloidal solution, it is made up of particles suspended in a fluid. It accounts for about 7% of the human body weight. The average adult has a blood volume of roughly 5 liters, composed of a fluid called plasma, and several kinds of cells. Within the blood plasma, are erythrocytes (red blood cells), leukocytes (white blood cells), thrombocytes (platelets) and other substances. The cells that make up the blood can be seen in **Figure** 22.26.

Plasma

Plasma is the golden-yellow liquid part of the blood. Plasma is 90% water and 10% dissolved materials including proteins, glucose, ions, hormones, and gases. It acts as a buffer, maintaining pH near 7.4. Plasma is about 54% the volume of blood; cells and fragments make up about 46% of the volume.

Red Blood Cells

Red blood cells, also known as **erythrocytes**, are flattened, doubly concave cells that carry oxygen. There are about 4 to 6 million cells per cubic millimeter of blood. Red blood cells make up about 45% of blood volume, as shown in **Figure** 22.27. Each red blood cell has 200 million hemoglobin molecules. Humans have a total of 25 trillion red blood cells (about 1/3 of all the cells in the body). Red blood cells are continuously made in the red marrow of long bones, ribs, skull, and vertebrae. Each red blood cell lives for only 120 days, after which they are destroyed in liver and spleen.

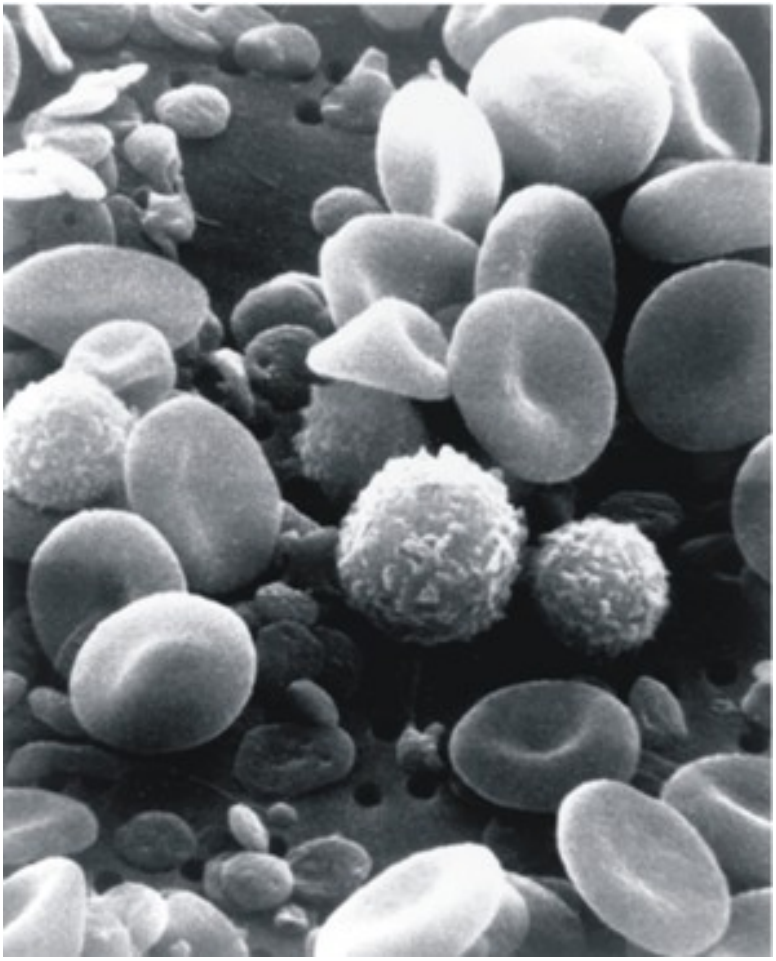


Figure 22.26: A scanning electron microscope (SEM) image of normal circulating human blood. One can see red blood cells, several white blood cells including knobby lymphocytes, a monocyte, a neutrophil, and many small disc-shaped platelets.

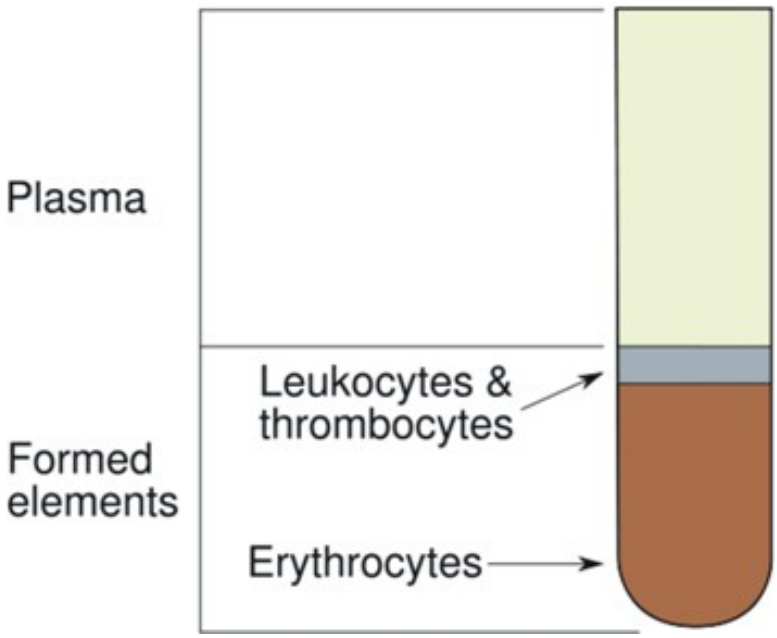


Figure 22.27: The components of blood. Red blood cells make up about 45% of the blood volume, white blood cells, about one percent, and platelets less than one percent. Plasma makes up the rest of the blood.

Mature red blood cells do not have a nucleus or other organelles. They contain the protein hemoglobin which gives blood its red color. The iron-containing heme portion of hemoglobin enables the protein to carry oxygen to cells. Heme binds to molecules of oxygen, which increases the ability of the blood to carry the gas.

Iron from hemoglobin is recovered and reused by red marrow. The liver degrades the heme units and secretes them as pigment in the bile, responsible for the color of feces. Each second two million red blood cells are produced to replace those thus taken out of circulation.

White Blood Cells

White blood cells, also known as **leukocytes**, are generally larger than red blood cells, as shown in **Figure** 22.28. They have a nucleus, but do not have hemoglobin. White blood cells make up less than one percent of the blood's volume. They are made from stem cells in bone marrow. They function in the cellular immune response. There are five types of white blood cells. Neutrophils enter the tissue fluid by squeezing through capillary walls and phagocytizing (swallowing) foreign bodies. Macrophages also swallow and destroy cell debris and bacteria or viruses. In **Figure** 22.29, a macrophage is shown phagocytizing two particles, possibly pathogens. Macrophages also release substances that cause the numbers of white blood cells to increase. Antigen-antibody complexes are swallowed by macrophages.

Lymphocytes fight infection. T-cells attack cells containing viruses. B-cells produce antibodies. To learn more about the role of white blood cells in fighting infection, refer to the *Immune System and Disease* chapter.

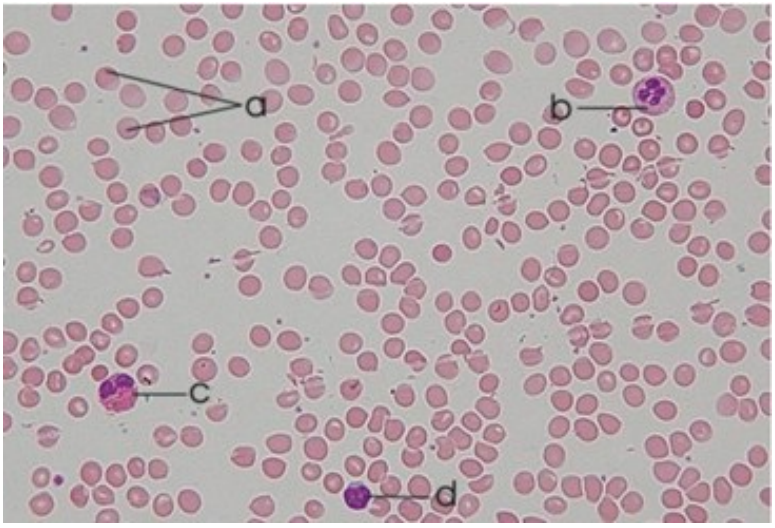


Figure 22.28: Relative sizes of red and white blood cells. a - red blood cells; b – neutrophil; c - eosinophil; d – lymphocyte. b, c, and d are different types of white blood cells.

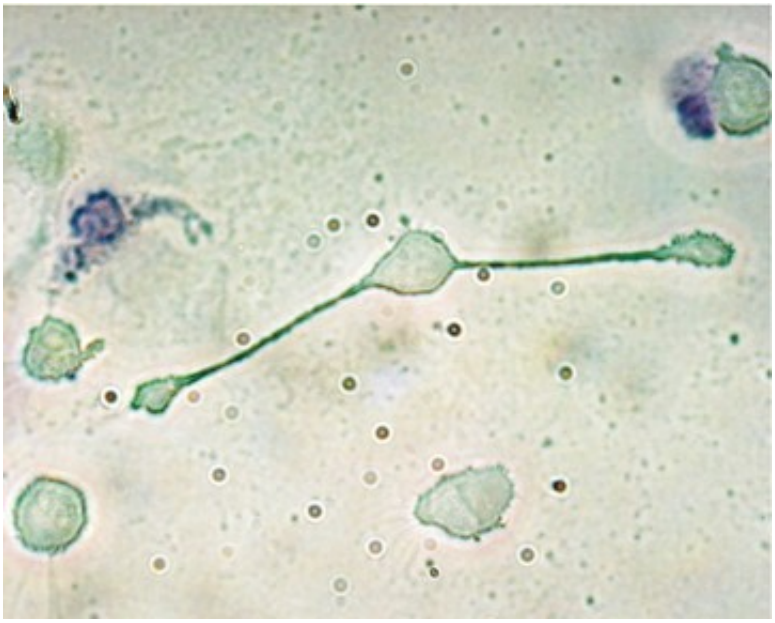


Figure 22.29: Macrophage showing cytoplasmic extensions that allow it to "swallow" particles or pathogens. In the image here, a mouse macrophage stretches its arms to engulf two particles at once.

Platelets

Platelets, also known as **thrombocytes**, are important in blood clotting. Platelets are cell fragments that bud off bone marrow cells called megakaryocytes. A platelet is shown in **Figure** 22.30. They make up less than one percent of blood volume. Platelets carry chemicals essential to blood clotting. They change fibrinogen into fibrin, a protein that creates a mesh onto which red blood cells collect, forming a clot. This clot stops more blood from leaving the body and also helps to prevent bacteria from entering the body. Platelets survive for 10 days before being removed by the liver and spleen. There are 150,000 to 300,000 platelets in each milliliter of blood. Platelets stick to tears in blood vessels and they release clotting factors.

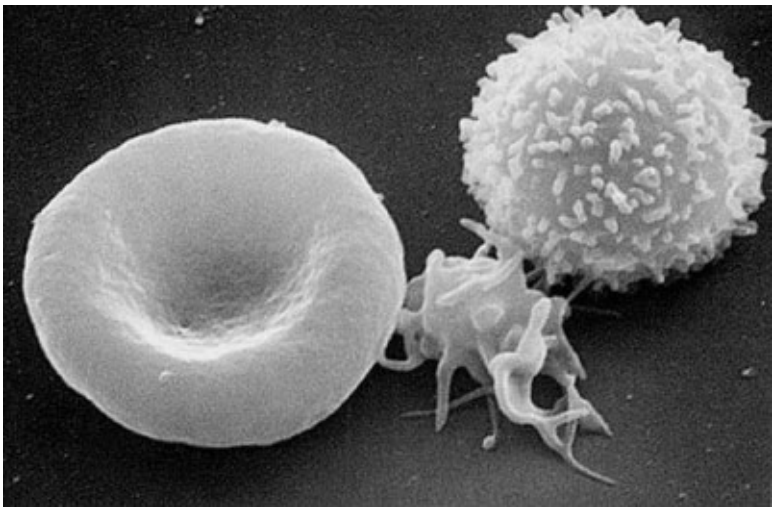


Figure 22.30: Cells of the blood. From left to right: Red blood cell, platelet, white blood cell. The concave side of red blood cells can be seen. Both sides of red blood cells are concave. The biconcave shape gives the red blood cells a smaller surface to volume ratio, which allows them to pick up large amounts of oxygen.

Other Blood Components

Blood plasma also contains other substances other than water. Some important components of blood include:

- Serum albumin: a plasma protein that acts as a transporter of hormones and other molecules.
- Antibodies: proteins that are used by the immune system to identify and destroy foreign objects such as bacteria and viruses.
- Hormones: chemical messengers that are produced by one cell and carried to another.
- Electrolytes such as sodium (Na+) and chloride (Cl-) ions.

Production and Breakdown of Blood Cells

Blood cells are produced in the red and yellow bone marrow in a process called **hematopoiesis**. Blood cells are broken down by the spleen and certain cells in the liver. The liver also clears some proteins, lipids and amino acids from the blood. The kidney actively secretes waste products of the blood into the urine.

Functions of Blood

Transport of Oxygen

The hemoglobin molecule is the major transporter of oxygen in mammals, including humans and many other species. About 98.5 percent of the oxygen in a sample of arterial blood in a healthy human is bonded with hemoglobin. Only 1.5 percent of the oxygen in blood is not carried by hemoglobin, instead it is dissolved in the plasma.

Under normal conditions in humans at rest, the hemoglobin in the red blood cells that are leaving the lungs is about 98 to 99 percent saturated with oxygen, and the blood is referred to as oxygenated. In a healthy adult at rest, deoxygenated blood returning to the lungs is still 75 percent saturated with oxygen. Oxygen saturation of arterial blood at or below 95 percent is considered dangerous in an individual at rest (for instance, during surgery under anesthesia)

Substances other than oxygen can bind to the hemoglobin; in some cases this can cause irreversible damage to the body. The gas carbon monoxide, for example, is very dangerous when absorbed into the blood. It bonds irreversibly with hemoglobin, which reduces the volume of oxygen that can be carried in the blood. Carbon monoxide poisoning can very quickly cause suffocation and death. Carbon monoxide is released during combustion (fire). It is released by cigarettes, barbeque grills, combustion of petrol products in cars and trucks, or anything else that can be burned.

Transport of Carbon Dioxide

When systemic arterial blood flows through capillaries, carbon dioxide diffuses from the tissues into the blood. Some carbon dioxide is dissolved in the blood. The remaining carbon dioxide is converted to bicarbonate and hydrogen ion which is then carried in the blood to the lungs, where it is converted back to carbon dioxide and released into the lungs.

Thermoregulation

Blood circulation transports heat through the body, and adjustments to this flow are an important part of thermoregulation. Increasing blood flow to the surface (e.g. during warm

weather or strenuous exercise) causes warmer skin, resulting in greater heat loss. Decreasing surface blood flow conserves heat.

Blood Clotting

Coagulation, or **blood clotting**, is a complex process by which blood forms solid clots. Coagulation is important to stop bleeding and begin repair of damaged blood vessels. Blood clotting disorders can lead to an increased risk of bleeding or clotting inside a blood vessel. Platelets are important for the proper coagulation of blood.

Clotting is started almost immediately when an injury damages the endothelium of a blood vessel. Platelets clump together, forming a plug at the site of injury. Then, proteins in the plasma called **coagulation factors**, respond in a series of chemical reactions that form a tough protein called **fibrin**. The fibrin strands form a web across the platelet plug, trapping red blood cells before they can leave through the wound site. This mass of platelets, fibrin, and red blood cells forms a clot that hardens into a scab.

Certain nutrients are needed for the proper functioning of the clotting mechanism. Two of these are calcium and vitamin K. Luckily for you, bacteria that live in your intestines make enough vitamin K so you do not need to have extra in your food.

Blood Types

Blood type (also called a **blood group**), is determined by the presence or absence of certain molecules, called antigens, on the surface of red blood cells. An **antigen** is a molecule or substance that causes an immune response. Blood type antigens may be proteins, or carbohydrates, depending on the blood group system. The antigens on a person's own body cells are recognized by their immune system as "self" antigens, and their immune system does not attack them. However, if a person is exposed to a blood group antigen that is different from their own blood group, the person's immune system will produce antibodies against the donor blood antigens. These antibodies can bind to antigens on the surface of transfused red blood cells (or other tissue cells) often leading to destruction of the cells by the immune system.

The erythrocyte surface antigens that have one allele, or a group of very closely linked genes, are collectively called a "blood group system". There are 29 known blood group systems in humans, but the ABO blood group system and the Rhesus (Rh) blood group system are the most important for blood transfusions.

ABO Blood Group System

In 1875, a German physiologist, Leonard Landois reported that the blood cells of a human and an animal would clump together when mixed. In the early 1900s, Austrian biologist and physician Karl Landsteiner pointed out that a similar clumping reaction occurred when the blood of one person was transfused with another. He determined that this might be the cause of shock, jaundice, and release of hemoglobin that had followed some earlier attempts at person-to-person blood transfusions.

In 1909, Landsteiner classified blood into the A, B, AB, and O groups. He also showed that transfusions between of the same blood group did not result in the destruction of blood cells and that clumping occurred only when a person was transfused with the blood of a person belonging to a different blood group.

The "A" and "B" of the ABO blood group refer to two carbohydrate antigens found on the surface of red blood cells. There is not an O antigen. Type O red blood cells do not have either type A or B antigens on their surface, as listed in **Table** 22.1. Antibodies are found in the blood plasma. The blood type of a person can be determined by using antibodies that bind to the A or B antigens of red blood cells.

Table 22.1: **Blood Types, Antigen Types, and Antibody Types**

Blood Type	Antigen Type	Serum (Plasma) Antibodies	Can Receive Blood from Types	Can Donate Blood to Types
A	A	anti-B	A, O	A, AB
B	B	anti-A	B, O	B, AB
AB	A and B	none	AB, A, B, O	AB
O	none	anti-A, anti-B	O	AB, A, B, O

(*Source:* CK12 Foundation, *License:* CC-BY-SA)

Agglutination is the clumping of red blood cells that occurs when different blood types are mixed together, shown in **Figure** 22.31. It involves a reaction between antigens on the surface of red blood cells and protein antibodies in the blood plasma. Mixing different blood types together can cause agglutination, a process that has been used as a way of determining a person's blood type.

Rhesus Blood Group System

The **Rhesus system** is the second most significant blood group system in human blood transfusion. The most significant Rhesus antigen is called the **RhD antigen**, also called Rhesus factor. A person either has, or does not have the RhD antigen on the surface of their

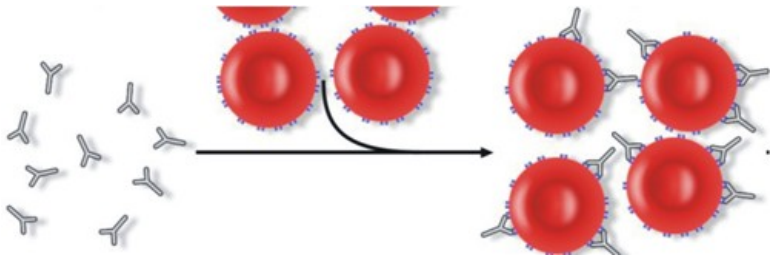


Figure 22.31: Antigens on the red blood cell surface. Antibodies attach to the antigens on the red blood cell, causing the blood cells to clump together. This leads to agglutination of the blood.

red blood cells. This is usually indicated by "RhD positive" (does have the RhD antigen) or "RhD negative" (does not have the antigen) suffix to the ABO blood group (see blood agglutination test in **Figure** 22.32).

The Rhesus system is named after the Rhesus monkey, in which the antigen was first discovered by Karl Landsteiner and Alexander S. Wiener in 1937. The importance of the Rh factor was realized soon after. Dr. Phillip Levine, a pathologist who worked at a New York hospital, made the connection between the Rh factor and the incidence of a blood disease in newborn babies. The disease, called hemolytic disease of the newborn is a condition that develops while the fetus is in the womb. If a mother is RhD negative, and the father is RhD positive, the fetus may inherit the dominant RhD positive trait from the father. The RhD negative mother can make antibodies against the RhD antigens of her developing baby. This can happen if some of the fetus' blood cells pass into the mother's blood circulation, or if the mother has received an RhD positive blood transfusion.

The fetus' red cells are broken down and the fetus can develop anemia. This disease ranges from mild to very severe, and fetal death from heart failure can occur. Most RhD disease can be prevented by treating the mother during pregnancy or soon after childbirth. The mother is injected with anti-RhD antibodies, so that the baby's red blood cells are destroyed before her body can produce antibodies against them. If a pregnant woman is known to have anti-RhD antibodies, the RhD blood type of a fetus can be tested by analysis of fetal DNA in maternal plasma to assess the risk to the fetus of Rh disease.

The presence or absence of the ABO group antigens and the RhD antigens are always determined for all recipient and donor blood. **Figure** 22.32 shows a routine way in which a person's ABO blood group is determined.

Blood Products

In order to provide maximum benefit from each blood donation and to extend shelf-life, blood banks separate some whole blood into several different products. Some of the most common

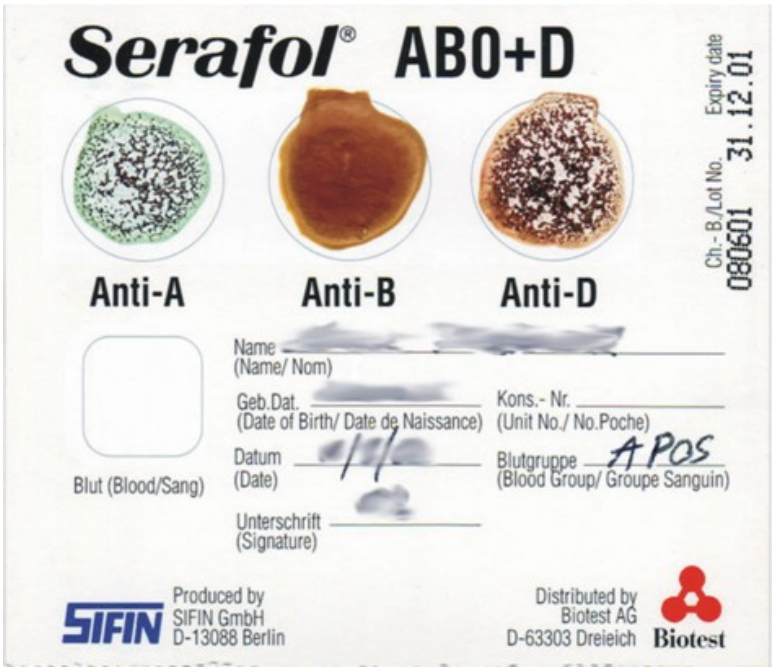


Figure 22.32: A bedside blood grouping card showing the agglutination of the blood with anti-A and anti-Rh(D), but not with anti-B. Therefore the blood group is A positive. This method of blood grouping relies on seeing an agglutination reaction to determine a person's blood group. The card has dried blood group antibody reagents fixed onto its surface. A drop of the person's blood is placed on each area on the card. The presence or absence of visual agglutination allows a quick method of determining the ABO and Rhesus group of the person.

of these products are packed red blood cells, plasma, platelets, and fresh frozen plasma. Units of packed red blood cells are made by removing as much of the plasma as possible from whole blood units. Clotting factors made by genetic engineering are now routinely used for the treatment of the clotting disorder hemophilia, so the risk of possible infection from donated blood products is avoided.

Universal Donors and Universal Recipients

Regarding the donation of packed red blood cells, individuals with type O negative blood are often called **universal donors**, and those with type AB positive blood are called **universal recipients**. Type O red blood cells do not have the A or B antigens, and can be given to people with a different ABO blood group. The blood plasma of an AB person does not contain any anti-A or anti-B antibodies, so they can receive any ABO blood type. The possible reactions of anti-A and anti-B antibodies in the donor blood to the recipient's red blood cells are usually not a problem because only a small volume of plasma that containing antibodies is given to the recipient. Refer to **Table** 22.1 for a complete listing of ABO antigens and antibodies that are involved in the ABO system.

In April 2007 researchers discovered a way to convert blood types A, B, and AB to O; the method used enzymes that removed the antigens on the surface of the red blood cells.

Other Blood Group Systems

You probably have heard a lot about the ABO and Rhesus (RhD) blood group systems by now, but you have probably not heard much about the other 27 other systems. Many other antigens are found on the cell membrane of red blood cells. For example, an individual can be AB RhD positive, and at the same time M and N positive (MNS system), K positive (Kell system), Le^a or Le^b negative (Lewis system), Duffy positive, or Duffy negative (Duffy system), and so on, being positive or negative for each blood group system antigen. Many of the blood group systems were named after the patients in whom the antibodies were first found.

Some blood group systems are associated with a disease, for example, the Kell antigen is associated with McLeod syndrome, a genetic disorder in which the red blood cells are spiky shaped. Certain other blood group systems may affect resistance to infections, an example being the resistance to specific malaria species seen in individuals who lack the Duffy antigen. The Duffy antigen is less common in ethnic groups from areas with a high incidence of malaria.

Rare blood types can cause supply problems for blood banks and hospitals. For example Duffy-negative blood occurs much more frequently in people of African origin, and the rarity of this blood type in the rest of the population can result in a shortage of Duffy-negative blood. Similarly, for RhD negative people, there is a risk associated with traveling to parts

of the world where supplies of RhD negative blood are rare, particularly East Asia.

Homeostatic Imbalances of the Blood

Problems can occur with red blood cells, white blood cells, platelets, and other components of the blood. Many blood disorders are genetic, they are inherited from a parent, some are a result of nutrient deficiency, while others are cancers of the blood.

Sickle-cell disease is a group of genetic disorders caused by abnormally shaped hemoglobin, called sickle hemoglobin. In many forms of the disease, the red blood cells change shape because the abnormal hemoglobin proteins stick to each other, causing the cell to get a rigid surface and sickle shape, shown in **Figure** 22.33. This process damages the membrane of the red blood cell, and can cause the cells to get stuck in blood vessels. This clotting causes oxygen starvation in tissues, which may cause organ damage such as stroke or heart attack. The disease is chronic and lifelong. Individuals are most often well, but their lives are punctuated by periodic painful attacks. Sickle-cell disease occurs more commonly in people (or their descendants) from parts of the world such as sub-Saharan Africa, where malaria is or was common. It also occurs in people of other ethnicities. As a result, those with sickle cell disease are resistant to malaria since the red blood cells are not favored by the malaria parasites. The mutated hemoglobin allele is recessive, meaning it must be inherited from each parent for the individual to have the disease.

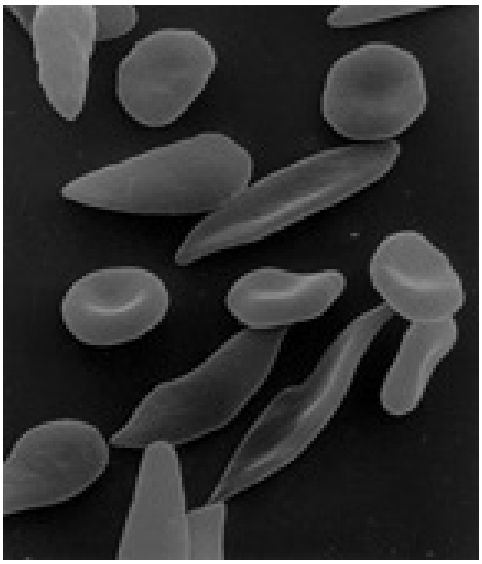


Figure 22.33: Sickle-cell disease. The abnormal shape of the red blood cells damages the red blood cells which causes them to get stuck in blood vessels. The blocked capillaries reduce the blood flow to an organ, and can result in pain and organ damage.

Iron deficiency anemia is the most common type of anemia. It occurs when the dietary

intake or absorption of iron is less than what is needed by the body. As a result, hemoglobin, which contains iron, cannot be made. In the United States, 20 percent of all women of childbearing age have iron deficiency anemia, compared with only 2 percent of adult men. The principal cause of iron deficiency anemia in premenopausal women is blood lost during menstruation.

Leukemia is a cancer that originates in the bone marrow and is characterized by an abnormal production of white blood cells (rarely red blood cells) that are released into the bloodstream. **Lymphoma** is a cancer of the lymphatic system, which helps to filter blood. Lymphoma can be categorized as either Hodgkin's lymphoma or non-Hodgkin's lymphoma.

Hemophilia is the name of a group of hereditary genetic diseases that affect the body's ability to control blood clotting. Hemophilia is characterized by a lack of clotting factors in the blood. Clotting factors are needed for a normal clotting process. When a blood vessel is injured, a temporary scab does form, but the missing coagulation factors prevent the formation of fibrin which is needed to maintain the blood clot. Therefore, a person who has hemophilia is initially able to make a clot to stop the bleeding, but because fibrin is not produced, the body is unable to maintain a clot for long. The risks of the re-bleeding of an injury and internal bleeding are increased in hemophilia, especially into muscles, joints, or bleeding into closed spaces.

Haemochromatosis is a hereditary disease that is characterized by a buildup of iron in the body. Iron accumulation can eventually cause end organ damage, most importantly in the liver and pancreas, manifesting as liver failure and diabetes mellitus respectively. It is estimated that roughly one in every 300-400 people is affected by the disease, primarily of Northern European and especially people of Irish, Scottish, Welsh and English descent.

Lesson Summary

- The functions of blood include the removal of wastes such as carbon dioxide, urea and lactic acid from the body tissues; defense of the body against infection by microorganisms or parasites; repair of damage to the body tissues; transport of chemical messages, such as hormones and hormone-like substances; control of body pH; control of body temperature.
- Within the blood plasma are the red blood cells, white blood cells, platelets, and other substances. Red blood cells are the most common types of cells in the blood, they make up about 45 percent of blood volume.
- Blood clotting begins when the endothelium of a blood vessel is torn. Platelets clump together, forming a plug at the site of injury. Then, the coagulation factors cause a series of chemical reactions that form fibrin. The fibrin strands form a web across the platelet plug, trapping red blood cells before they can leave through the wound site. This mass of platelets, fibrin, and red blood cells forms a clot that hardens into a scab.
- There are 29 blood group systems, but the two major ones are the ABO and Rhesus

systems.

- The ABO system is of great importance in blood transfusions. Individuals with type O negative blood are called universal donors, and those with type AB positive blood are called universal recipients. Type O red blood cells do not have the A or B antigens, and can be given to people with a different ABO blood group. The blood plasma of an AB person does not contain any anti-A or anti-B antibodies, so they can receive any ABO blood type.
- Iron deficiency anemia is the most common type of anemia. It occurs when the dietary intake or absorption of iron is less than what is needed by the body. As a result, hemoglobin, which contains iron, cannot be made. Hemophilia is the name of a group of hereditary genetic diseases that affect the body's ability to control blood clotting. Hemophilia is characterized by a lack of clotting factors in the blood.

Review Questions

1. Name the four main components of blood.
2. How does the structure of a red blood cell relate to its function?
3. Name one other gas that can bind to hemoglobin, and identify an affect that such binding can have on homeostasis.
4. Why might iron-deficiency anemia cause a person to feel tired?
5. Identify two different types of human blood systems.
6. Identify the processes involved in blood clotting.
7. A sample of blood taken from a patient has elevated (higher than normal) levels of leucocytes. What could this mean?
8. Identify where in the body red blood cells and white blood cells are made.
9. Explain why taking erythropoietin (EPO), which stimulates the production of more red blood cells, is considered a form of cheating in sports.

Further Reading / Supplemental Links

- http://www.estrellamountain.edu/faculty/farabee/biobk
- http://waynesword.palomar.edu/aniblood.htm
- http://en.wikipedia.org

Vocabulary

agglutination The clumping of red blood cells that occurs when different blood types are mixed together.

antibodies Proteins that are used by the immune system to identify and destroy foreign objects such as bacteria and viruses.

blood A fluid connective tissue; arterial blood carries oxygen and nutrient to all the body's cells, and venous blood carries carbon dioxide and other metabolic wastes away from the cells.

blood type (blood group) Determined by the presence or absence of certain molecules, called antigens, on the surface of red blood cells.

coagulation Blood clotting, a complex process by which blood forms solid clots.

coagulation factors Proteins in the plasma which respond damage to a blood vessel; response includes a series of chemical reactions that form a tough protein called fibrin.

erythrocytes Red blood cells; flattened, doubly concave cells that carry oxygen.

haemochromatosis A hereditary disease that is characterized by a buildup of iron in the body; can eventually cause end organ damage, most importantly in the liver and pancreas, manifesting as liver failure and diabetes mellitus respectively.

hematopoiesis The production of blood cells in the red and yellow bone marrow.

heme The iron-containing portion of hemoglobin; enables the protein to carry oxygen to cells.

hemoglobin Protein in red blood cells that carries oxygen.

hemophilia The name of a group of hereditary genetic diseases that affect the body's ability to control blood clotting.

hormones Chemical messengers that are produced by one cell and carried to another.

leukemia A cancer that originates in the bone marrow and is characterized by an abnormal production of white blood cells.

leukocytes White blood cells; function in the cellular immune response; includes neutrophils, eosinophils, and macrophages.

lymphoma A cancer of the lymphatic system, which helps to filter blood; can be categorized as either Hodgkin's lymphoma or non-Hodgkin's lymphoma.

plasma The golden-yellow liquid part of the blood; 90% water and 10% dissolved materials including proteins, glucose, ions, hormones, and gases.

serum albumin A plasma protein that acts as a transporter of hormones and other molecules.

sickle-cell disease A group of genetic disorders caused by abnormally shaped hemoglobin, called sickle hemoglobin.

thrombocytes Platelets; important in blood clotting; cell fragments that bud off bone marrow cells called megakaryocytes.

universal donors Individuals with type O negative blood.

universal recipients Individuals with type AB positive blood.

Points to Consider

- How might the composition of your blood change during a 24-hour period?
- What do you think is the relationship between the cardiovascular system, blood, and the respiratory system?

22.3 Lesson 22.3: Respiratory System

Lesson Objectives

- Distinguish between external and internal respiration.
- Identify the structures of the respiratory system.
- Outline the process of inhalation.
- Describe how carbon dioxide is carried in the blood.
- Compare the causes of emphysema and asthma.

Introduction

Have you ever wondered what it would be like to have gills? You would breathe and look very different from the rest of us, but they would be great for swimming and diving! Despite such differences, the main functions of lungs and gills are the same: to obtain oxygen, and to release carbon dioxide.

The human respiratory system brings oxygen, O_2, into the body and releases carbon dioxide, CO_2, into the atmosphere. Oxygen is drawn in through the respiratory tract, which is shown in **Figure** 22.34, and is then delivered to the blood. This process is called **external respiration**. The exchange of gases between the blood and the cells of the body is called **internal respiration**.

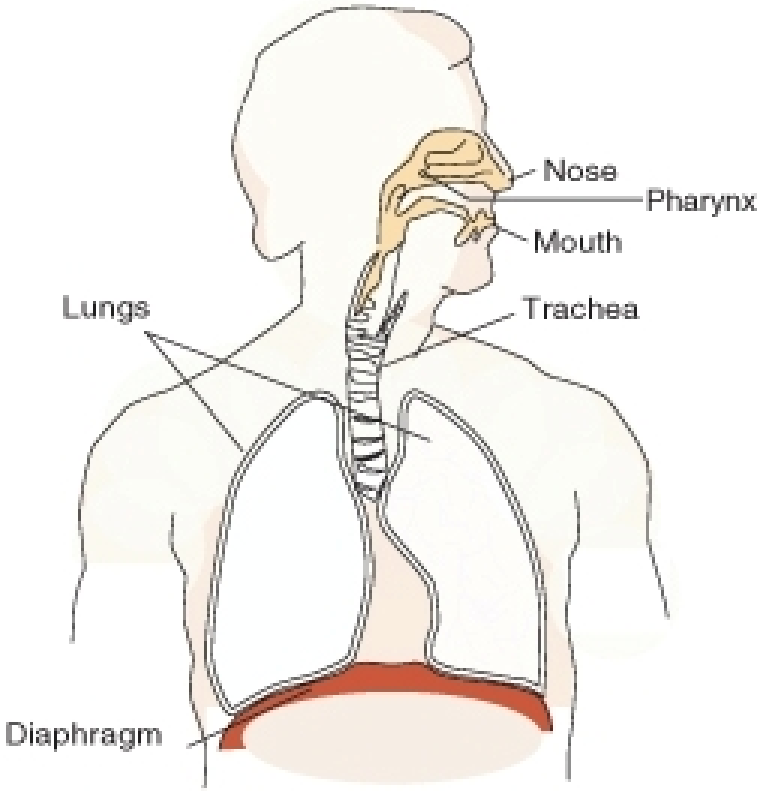


Figure 22.34: The respiratory system. Air moves down the trachea, a long straight tube in the chest. The diaphragm pulls air in and pushes it out. Respiratory systems of various types are found in a wide variety of organisms.

Comparing "Cellular Respiration" and "Respiration"

Respiration is the transport of oxygen from the outside air to the cells of the body, and the transport of carbon dioxide in the opposite direction. This is in contrast to the biochemical definition of respiration, which refers to cellular respiration. **Cellular respiration** is the metabolic process by which an organism obtains energy by reacting oxygen with glucose to give water, carbon dioxide and ATP (energy). Although respiration is necessary to sustain cellular respiration and thus life in animals, the processes are very different. Cellular respi-

ration takes place in individual cells of the animal, while respiration involves the transport of metabolites between the organism and external environment.

Structures of the Respiratory System

The nose and **nasal cavity** filter, warm, and moisten the inhaled air. The nose hairs and mucus produced by the epithelial cells in the nose catch airborne particles and prevent them from reaching the lungs.

Behind the nasal cavity, air next passes through the **pharynx**, a long tube that is shared with the digestive system. Both food and air pass through the pharynx. A flap of connective tissue called the **epiglottis** closes over the trachea when food is swallowed to prevent choking or inhaling food. In humans the pharynx is important in vocalization

The **larynx**, also called the voicebox, is found just below the point at which the pharynx splits into the trachea and the esophagus, shown in **Figure** 22.35. The voice is generated in the larynx. Air from the lungs is needed for the vocal folds to produce speech.

The **trachea**, or wind pipe, is a long tube that leads down to the chest where it divides into the right and left **bronchi** in the lungs. The bronchi branch out into smaller bronchioles, which are the first airway passages that do not contain cartilage. The bronchioles lead into the **alveoli**, which are the multi-lobed sacs in which most of the gas exchange occurs.

The Journey of a Breath of Air

In air-breathing vertebrates such as humans, respiration of oxygen includes four stages:

1. Ventilation from the atmosphere into the alveoli of the lungs.
2. Pulmonary gas exchange from the alveoli into the pulmonary capillaries.
3. Gas transport from the pulmonary capillaries through the circulation to the peripheral capillaries in the organs.
4. Peripheral gas exchange from the tissue capillaries into the cells and mitochondria.

Ventilation: From the Air to the Alveoli

Air enters the body through the nose, is warmed, filtered, and passed through the nasal cavity. Air passes the pharynx (which has the epiglottis that prevents food from entering the trachea). The upper part of the trachea contains the larynx. The vocal cords are two bands of tissue that extend across the opening of the larynx. After passing the larynx, the air moves into the trachea. The trachea is a long tube that divides into two smaller tubes called bronchi which lead into each lung, shown in **Figure** 22.35. Bronchi are reinforced to prevent their collapse and are lined with ciliated epithelium and mucus-producing cells.

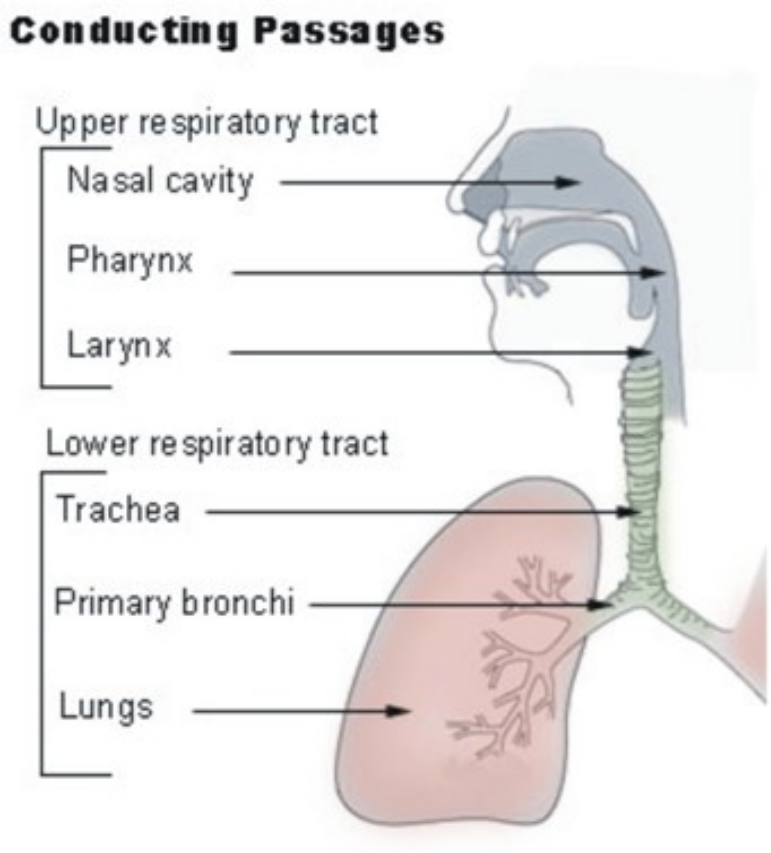


Figure 22.35: The structures of the respiratory system include the nasal cavity, the pharynx, larynx, which together are the upper respiratory tract. The trachea, bronchi, bronchioles and alveoli are part of up the lower respiratory tract.

Bronchi branch into smaller and smaller tubes called bronchioles. Bronchioles end in grape-like clusters called alveoli. Alveoli are surrounded by a network of thin-walled capillaries, shown in **Figure** 22.36.

Breathing in, or inhaling, is usually an active movement, contraction of the diaphragm muscles uses ATP. The **diaphragm** is a muscle that is found below the lungs (shown in **Figure** 22.34). Contraction of the diaphragm causes the volume of the chest cavity to increase, and the air pressure within the lungs to decrease. The pressure difference causes air to rush into the lungs. Relaxation of the diaphragm causes the lungs to recoil and air is pushed out of the lungs. Breathing out, or exhaling, is normally a passive process powered by the elastic recoil of the chest, similar to letting the air out of a balloon.

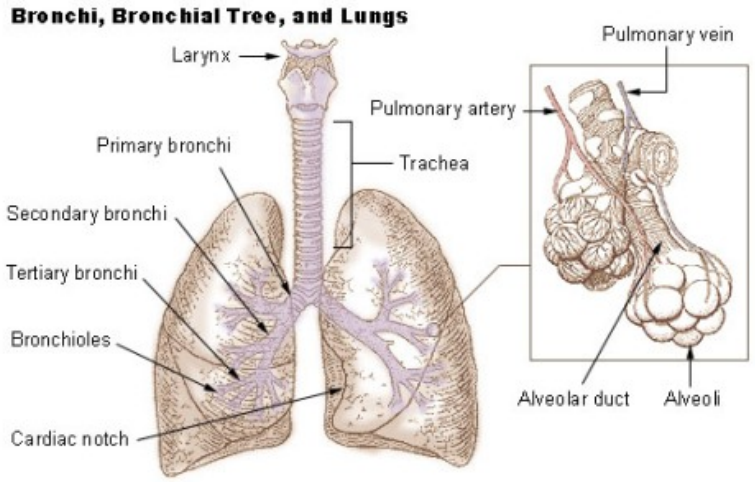


Figure 22.36: The alveoli are the tiny grape-like structures within the lungs, and are the site of pulmonary gas exchange.

Pulmonary Gas Exchange: From the Alveoli into the Pulmonary Capillaries

Breathing is only part of the process of delivering oxygen to where it is needed in the body. The process of **gas exchange** occurs in the alveoli by diffusion of gases between the alveoli and the blood passing in the lung capillaries, as shown in **Figure** 22.37. Recall that diffusion is the movement of substances from an area of higher concentration to an area of lower concentration. The difference between the high concentration of O_2 in the alveoli and the low O_2 concentration of the blood in the capillaries is enough to cause O_2 molecules to diffuse across the thin walls of the alveoli and capillaries and into the blood. CO_2 moves out of the blood and into the alveoli in a similar way. The greater the concentration difference, the greater the rate of diffusion.

Breathing also results in loss of water from the body. Exhaled air has a relative humidity

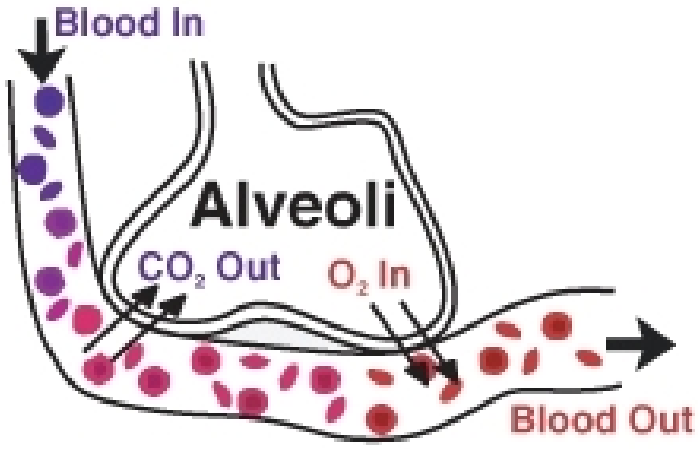


Figure 22.37: Gas exchange happens in the lungs through diffusion. Deoxygenated blood has a high concentration of CO and a low O concentration. CO moves out of the blood and into the alveoli, where the concentration of CO is lower. Likewise, O moves from an area of higher concentration (the alveoli), to an area of lower concentration (the blood).

of 100 percent because of the diffusion of water that from the moist surface of the breathing passages and the alveoli into the warm exhaled air.

In the lungs, oxygen is transported across the thin membranes of the alveoli and the border of the capillary and attracted to the hemoglobin molecule within the red blood cell.

After leaving the lungs, the oxygenated blood returns to the heart to be pumped through the aorta and around the body. The oxygenated blood travels through the aorta, to the smaller arteries, arterioles, and finally to the peripheral capillaries where gas exchange occurs.

Peripheral Gas Exchange: From Capillaries into Cells, and from Cells into Capillaries

The oxygen concentration in body cells is low, while the blood that leaves the lungs is 97 percent saturated with oxygen. So, oxygen diffuses from the blood into the body cells when it reaches the peripheral capillaries (the capillaries in the systemic circulation).

Carbon dioxide concentration in metabolically active cells is much greater than in capillaries, so carbon dioxide diffuses from the cells into the capillaries. Most of the carbon dioxide (about 70 percent) in the blood is in the form of bicarbonate (HCO_3^-). A small amount of carbon dioxide dissolves in the water in the plasma to form carbonic acid (H_2CO_3). Carbonic acid and bicarbonate play an important role in regulating the pH of the body.

In order to remove CO_2 from the body, the bicarbonate is picked up by a red blood cell, and is again turned in to carbonic acid. A water molecule (H_2O) is then taken away from the

carbonic acid, and the remaining CO_2 molecule is expelled from the red blood cells and into the alveoli where it is exhaled. The following equation shows this process:

$HCO_3^- + H^+ \quad H_2CO_3 \quad CO_2 + H_2O$

Gas exchange between your body and the environment occurs in the alveoli. The alveoli are lined with pulmonary capillaries, the walls of which are thin enough to permit the diffusion of gases. Inhaled oxygen diffuses into the pulmonary capillaries, where it binds to hemoglobin in the blood. Carbon dioxide diffuses in the opposite direction, from capillary blood to alveolar air. At this point, the pulmonary blood is oxygen-rich, and the lungs are primarily holding carbon dioxide. Exhalation follows, thereby ridding the body of the carbon dioxide and completing the cycle of respiration.

Gas Exchange and Homeostasis

The equilibrium between carbon dioxide and carbonic acid is very important for controlling the acidity of body fluids. As gas exchange occurs, the pH balance of the body is maintained as part of homeostasis. If proper respiration is interrupted two things can occur:

1. Respiratory acidosis, in which arterial blood contains too much carbon dioxide, causing a drop in blood pH.
2. Respiratory alkalosis results from increased respiration (or hyperventilation) which causes a drop in the amount of carbon dioxide in the blood plasma. The drop in carbon dioxide concentration causes the blood pH to rise.

Control of Breathing by the Nervous System

Breathing is one of the few bodily functions which, within limits, can be controlled both consciously and unconsciously. Conscious attention to breathing is common in activities such as yoga, swimming, and karate. In speech or vocal training, a person learns to discipline his or her breathing for purposes other than life support.

Muscular contraction and relaxation controls the rate of expansion and constriction of the lungs. These muscles are controlled by the autonomic nervous system from the parts of the brainstem that control breathing: the medulla and the pons. This area of the brainstem forms the respiration regulatory center. When carbon dioxide levels increase in the blood (in the form of carbonic acid), such as during exercise, the pH level of the blood drops. This causes the medulla to send nerve impulses to the diaphragm and the muscles between the ribs, causing them to contract and increase the rate of breathing. This automatic control of respiration can be impaired in premature babies, or by drugs or disease.

Without breathing, the body's oxygen levels drop dangerously low within minutes, leading to permanent brain damage followed by death. It is not possible for a healthy person to

voluntarily stop breathing indefinitely. If we do not inhale, the level of carbon dioxide builds up in our blood and we experience great air hunger. Eventually, not breathing leads to a loss of consciousness at which time the autonomic nervous system takes control and initiates breathing.

Inhalation

Inhalation is started by the diaphragm and supported by the external intercostal muscles (the muscles that are between the ribs). It is an active process that needs ATP. When the diaphragm contracts, the ribcage expands and the contents of the abdomen are moved downward. This results in a larger thoracic (chest) volume, which in turn causes a decrease in air pressure inside the lungs. As the pressure in the chest falls, air from outside the body moves into the respiratory system. Normal resting respirations are 10 to 18 breaths per minute. During an average breath, an adult will exchange from 500 ml to 700 ml of air. The average breath capacity of a person is called **lung volume**, or tidal volume.

Exhalation

Exhalation is generally a passive process, however active, or forced, exhalation is carried out by the abdominal and the internal intercostal muscles. The lungs have a natural elasticity and as they recoil from the stretch of inhalation, air flows out of the lungs until the pressures in the chest and the atmosphere reach equilibrium. During forced exhalation, as when blowing out a candle, expiratory muscles including the abdominal muscles and internal intercostal muscles generate pressure in the chest and abdomen, which forces air out of the lungs.

Homeostatic Imbalances of the Respiratory System: Diseases and Disorders

Respiratory disease is the term for diseases of the lung, bronchial tubes, trachea and throat. These diseases range from mild, such as a cold, to being possibly life-threatening, such as bacterial pneumonia.

Respiratory diseases can be grouped as either obstructive (conditions which lower the rate of the airflow into and out of the lungs, such as in asthma) or restrictive (conditions that cause a reduction in the functional volume of the lungs, such as emphysema.)

Emphysema is a chronic lung disease caused by loss of elasticity of the lung tissue. The destruction of elastic structures that support the alveoli and the capillaries that feed the alveoli cause them to become hard and stiff. Eventually the walls of the alveoli break down and the alveoli become larger. The amount of oxygen that can enter the blood with each breath is reduced because the large alveoli cannot function efficiently; much of the oxygen that gets into the large alveoli cannot be absorbed into the blood so the oxygen is unused.

Symptoms include shortness of breath on exertion (usually when climbing stairs or a hill, and later at rest), and an expanded chest. Damage to the alveoli, which can be seen in **Figure** 22.38, is irreversible. Smoking is a leading cause of emphysema.

Figure 22.38: The inside of a lung showing the characteristics of emphysema due to smoking. Instead of alveoli, the cut surface shows multiple cavities lined by heavy black carbon deposits.

Bronchitis is an inflammation of the bronchi. Acute bronchitis is usually caused by viruses or bacteria and may last several days or weeks. Acute bronchitis is characterized by cough and phlegm (mucus) production. Symptoms are related to the inflammation of the airways and phlegm production, and include shortness of breath and wheezing. Chronic bronchitis is not necessarily caused by infection and is generally part of a syndrome called chronic obstructive pulmonary disease (COPD). Chronic bronchitis is defined clinically as a persistent cough that produces phlegm and mucus, for at least three months in two consecutive years.

Asthma is a chronic illness in which the airways narrow and becomes inflamed, as shown in **Figure** 22.39. Excessive amounts of mucus are also made by the lungs. Asthma often happens in response to one or more triggers. It may be triggered by exposure to an allergen such as mold, dust, or pet hair. It can also be caused by cold air, warm air, moist air, exercise, or emotional stress. In children, the most common triggers are viral illnesses such as those that cause the common cold. This airway narrowing causes symptoms such as wheezing, shortness of breath, chest tightness, and coughing. Some people with asthma, especially children, can become very frightened by the symptoms, which may cause even more breathing distress. Between asthma attacks, most patients feel well but can have mild symptoms and may remain short of breath after exercise for longer periods of time than a person who does not have asthma. The symptoms of asthma, which can range from mild to life threatening, can usually be controlled with a combination of medicines and environmental changes.

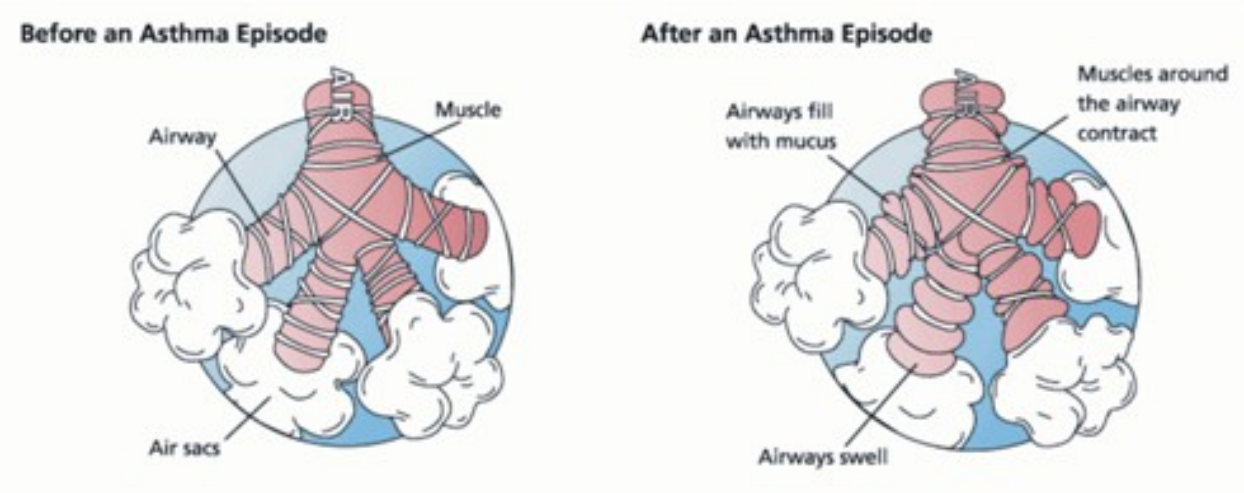


Figure 22.39: Asthma narrows the airways by causing allergy-induced spasms of surrounding muscles, narrowing of the airway, and excessive production of phlegm (mucus), which clogs the airways. The airway constriction responds to medicines called bronchodilators which relax the muscles. The feeling of breathlessness is somewhat like being able to breath only through a straw while walking.

Public attention in the developed world has recently focused on asthma because of the increasing numbers of cases, affecting up to one in four children who live in cities.

Pneumonia is an illness in which the alveoli become inflamed and flooded with fluid. Effective gas exchange cannot happen across the alveoli membranes. Pneumonia can result from a variety of causes, including infection with bacteria, viruses, fungi, or parasites, and chemical or physical injury to the lungs. Symptoms of pneumonia include cough, chest pain, fever, and difficulty in breathing. Treatment depends on the cause of pneumonia; bacterial pneumonia is treated with antibiotics.

Pneumonia is a common illness which occurs in all age groups, and is a leading cause of death among the elderly and people who are chronically and terminally ill. Vaccines to prevent certain types of pneumonia are available.

Tuberculosis (TB) is a common and deadly infectious disease caused by a type of bacteria called *Mycobacterium tuberculosis.* TB most commonly attacks the lungs (as pulmonary TB) but can also affect the central nervous system, the lymphatic system, the circulatory system, the genitourinary system, bones, joints and even the skin.

Over one-third of the world's population has been exposed to the TB bacterium. Not everyone infected develops the disease, so TB infection without symptoms (called a latent infection) is most common. However, one in ten latent infections will progress to active TB disease, which, if left untreated, kills more than half of its victims.

The rise in HIV infections and the neglect of TB control programs have led to an increase

in cases of tuberculosis. The development of drug-resistant strains has also contributed to this new epidemic. For example, between 2000 and 2004, about 20 percent of TB cases were resistant to standard antibiotic treatments. TB incidence varies widely, even in neighboring countries, apparently because of differences in health care system standards. A TB vaccine, called Bacille Calmette-Guérin (BCG), is available to people in some countries. The BCG is prepared from a strain of weakened live mycobacterium, which has lost its virulence in humans. The effectiveness of the BCG is a matter of debate among researchers, and the governments in some countries, including the United States, do not require people to get the BCG vaccination.

Lung cancer is a disease where epithelial (internal lining) tissue in the lung grows out of control. This leads to invasion of nearby tissue and growth of the tumor beyond the lungs. Lung cancer, which is the most common cause of cancer-related death in men and the second most common in women, is responsible for 1.3 million deaths worldwide every year The most common symptoms are shortness of breath, coughing (including coughing up blood), and weight loss.

The most common cause of lung cancer is exposure to tobacco smoke. The occurrence of lung cancer in non-smokers, who account for less than 10 percent of cases, appears to be due to a combination of genetic factors. Radon gas, asbestos, and air pollution may also contribute to lung cancer.

Asbestos is a mineral that was once used as a fire retardant in buildings and electrical wiring. The inhalation of asbestos fibers can cause a variety of lung diseases, including lung cancer. Tobacco smoking and exposure to asbestos greatly increase a person's chance of developing lung cancer.

Lesson Summary

- The main functions of lungs are to obtain oxygen, and to release carbon dioxide. Oxygen is drawn in through the respiratory tract and is then delivered to the blood in a process called external respiration. The exchange of gases between the blood and the cells of the body is celled internal respiration.
- The structures of the respiratory systems include the nose and nasal cavity, the pharynx, the larynx, (also called the voicebox), the trachea (also called the wind pipe), the right and left bronchi in the lungs, and the bronchioles that end in the alveoli.
- During inhalation, the diaphragm contracts, causing the volume of the chest cavity to increase. As a result, the air pressure within the lungs decreases. The pressure difference causes air to rush into the lungs. Relaxation of the diaphragm causes the lungs to recoil and air is pushed out of the lungs, which causes exhalation.
- Most of the carbon dioxide (about 70 percent) in the blood is in the form of bicarbonate (HCO_3^-). A small amount of carbon dioxide dissolves in the water in the plasma to form carbonic acid (H_2CO_3). When CO_2 enters the blood from body cells, it combines

with water in the plasma to produce carbonic acid (H_2CO_3), which is then turned into bicarbonate (HCO_3^-). The bicarbonate is then picked up by a red blood cell and turned back in to carbonic acid. A water molecule (H_2O) is then taken away from the carbonic acid, and the remaining CO_2 molecule is expelled from the red blood cells and into the lungs.

- Emphysema is a chronic lung disease caused by loss of elasticity of the lung tissue. The destruction of elastic structures that support the alveoli and the capillaries that feed the alveoli cause them to become hard and stiff. It is often caused by smoking. Asthma is also a chronic condition, which is often triggered by such things as exposure to an allergen, cold air, warm air, moist air, exercise, or emotional stress. The airways can constrict and become inflamed, and an excessive amount of mucus is produced. Airway narrowing causes symptoms such as wheezing, shortness of breath, chest tightness, and coughing.

Review Questions

1. Identify the respiratory structures through which air flows.
2. How is the diaphragm involved in breathing?
3. Compare respiration and cellular respiration.
4. Outline how most carbon dioxide is carried in the blood.
5. Why is it important for a pregnant woman to know her Rhesus blood type, and the Rh blood type of the father of her baby?
6. What is the difference between internal and external respiration?
7. What happens during an asthma attack?
8. Outline how emphysema affects the absorption of oxygen.
9. Where does the exchange of oxygen occur in the lungs?
10. What factors regulate breathing rate?

Further Reading / Supplemental Links

- http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookRESPSYS.html
- http://en.wikipedia.org

Vocabulary

alveoli Multi-lobed sacs in which most of the gas exchange occurs.

asthma A chronic illness in which the airways narrow and becomes inflamed.

bronchitis An inflammation of the bronchi.

diaphragm A muscle that is found below the lungs; contraction of the diaphragm causes the volume of the chest cavity to increase, and the air pressure within the lungs to decrease.

emphysema A chronic lung disease caused by loss of elasticity of the lung tissue.

external respiration Process in which oxygen is drawn in through the respiratory tract and is then delivered to the blood.

gas exchange The diffusion of gases between the alveoli and the blood passing in the lung capillaries; also the diffusion of gases from capillaries into cells, and from cells into capillaries throughout the body (peripheral gas exchange).

internal respiration The exchange of gases between the blood and the cells of the body.

larynx Found just below the point at which the pharynx splits into the trachea and the esophagus; also called the voice box.

lung cancer A disease where epithelial (internal lining) tissue in the lung grows out of control; leads to invasion of nearby tissue and growth of the tumor beyond the lungs.

lung volume (tidal volume) The average breath capacity of a person.

obstructive Conditions which lower the rate of the airflow into and out of the lungs, such as in asthma.

pharynx A long tube that is shared with the digestive system; both food and air pass through the pharynx.

pneumonia An illness in which the alveoli become inflamed and flooded with fluid.

respiration The transport of oxygen from the outside air to the cells of the body, and the transport of carbon dioxide in the opposite direction.

respiratory acidosis Condition in which arterial blood contains too much carbon dioxide, causing a drop in blood pH.

respiratory alkalosis Condition which results from increased respiration (or hyperventilation) which causes a drop in the amount of carbon dioxide in the blood plasma; the drop in carbon dioxide concentration causes the blood pH to rise.

respiratory disease The term for diseases of the lung, bronchial tubes, trachea and throat.

restrictive Conditions that cause a reduction in the functional volume of the lungs, such as emphysema.

trachea A long tube that leads down to the chest where it divides into the right and left bronchi in the lungs; also called the windpipe.

tuberculosis (TB) A common and deadly infectious disease caused by a type of bacteria called *Mycobacterium tuberculosis*; most commonly attacks the lungs, but can also affect the central nervous system, the lymphatic system, the circulatory system, the genitourinary system, bones, joints and even the skin.

Points to Consider

- How might the amount of oxygen in the air affect your respiratory and circulatory systems?
- Can you identify any structures that are part of both the respiratory and digestive systems?

Image Sources

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Chapter 23

Digestive and Excretory Systems

23.1 Lesson 23.1: Food and Nutrients

Lesson Objectives

- Identify classes of macronutrients and describe their roles in the body.
- Describe balanced eating and explain how it helps prevent obesity.
- State functions and food sources of vitamins and minerals.
- Describe eating disorders, their causes, and treatment.

Introduction

Did you ever hear the saying, "You are what you eat"? It's not just a saying. It's actually true. What you eat plays an important role in your health. Eating a variety of healthful foods promotes good physical health and provides energy for growth and activity. Many common diseases and their symptoms can be prevented or helped with healthful eating. Knowing what your body needs can help you choose foods to meet those needs.

Nutrients, Energy, and Building Materials

Nutrients are chemical elements or compounds that the body needs for normal functioning and good health. There are six main classes of nutrients: carbohydrates, proteins, lipids, water, vitamins, and minerals. The body needs these nutrients for three basic purposes: energy, building materials, and control of body processes.

A steady supply of energy is needed by cells for all body functions. Carbohydrates, proteins, and lipids provide this energy. Chemical bonds in molecules of these nutrients contain energy. When the bonds are broken during digestion to form simpler molecules, the energy

is released. Energy is measured in units called kilocalories (kcal), commonly referred to as Calories.

Molecules that make up the body are continuously broken down or used up, so they must be replaced. Some nutrients, particularly proteins, provide the building materials for this purpose. Other nutrients—including proteins, vitamins, and minerals—are needed to regulate body processes. One way is by helping to form enzymes. Enzymes are compounds that control the rate of chemical reactions in the body.

Nutrients can be classified in two groups based on how much of them the body needs:

- **Macronutrients** are nutrients that the body needs in relatively large amounts. They include carbohydrates, proteins, lipids, and water.
- **Micronutrients** are nutrients the body needs in relatively small amounts. They include vitamins and minerals.

The exact amount of a macronutrient an individual needs depends on many factors, including gender and age. Recommended daily intakes of three macronutrients for young people of both genders are shown in **Table** 23.1.

Table 23.1: **Recommended Daily Intakes of Carbohydrates, Proteins, and Water**

GenderAnd Age	Carbohydrates(grams/day)	Proteins(grams/day)	Water*(liters/day)
Males 9–13 years	130	34	2.4
14–18 years	130	52	3.3
Females 9–13 years	130	34	2.1
14–18 years	130	46	2.3

- Includes water in foods as well as beverages

Carbohydrates

Carbohydrates are organic (or carbon-containing) compounds consisting of the elements carbon, hydrogen, and oxygen. The elements are arranged in small molecules called saccharides. Carbohydrates are classified as either simple or complex, based on the number of saccharides they contain.

Simple carbohydrates contain just one or two saccharides. They are all sugars. Examples of sugars in the diet include fructose, which is found in fruit, and lactose, which is found in milk. The main function of simple carbohydrates is to provide the body with energy. One gram of carbohydrate provides four kilocalories of energy. Glucose is the sugar that is used most easily by cells for energy. It circulates in the blood, providing energy to cells

throughout the body. Glucose is the only source of energy used by the brain.

Complex carbohydrates, called polysaccharides, generally contain many saccharides. They include starches and fiber. Starches are found in plant foods such as vegetables and grains. They are broken down during digestion to form sugars that provide energy. Fiber consists of indigestible starches and other materials such as cellulose. It is present in all plant foods.

Fiber may be soluble or insoluble.

- Soluble fiber dissolves in water as it passes through the large intestine. It helps form substances that keep blood levels of glucose stable and blood levels of harmful lipids low (see below).
- Insoluble fiber does not dissolve but attracts water as it passes through the large intestine. This helps keep waste moist and moving easily through the intestine.

Proteins

Proteins are relatively large organic compounds containing carbon, hydrogen, oxygen, and nitrogen. The elements are arranged in small molecules called amino acids. Amino acids are the building blocks of proteins. They bond together to form long chains, called polypeptides. Proteins consist of one or more polypeptides.

Proteins play many vital roles in the body, including:

- Making up the majority of muscle tissue.
- Regulating many body processes.
- Forming antibodies that destroy bacteria and other "foreign invaders."
- Regulating the salt-water and acid-base balance in body fluids.
- Transporting nutrients and other vital substances in the blood.

Dietary proteins are broken down during digestion to provide the amino acids that cells need to make proteins for the body. Twenty different amino acids are needed for this purpose. Ten of these amino acids can be synthesized by cells from simple components. The other ten cannot be synthesized and must be obtained from foods. They are called essential amino acids because they are essential in the diet.

Proteins that contain all ten essential amino acids are referred to as complete proteins. They are found in animal foods such as milk and meat. Proteins that are missing one or more essential amino acids are referred to as incomplete proteins. They are found in plant foods such as legumes and rice. By eating a variety of different plant foods containing incomplete proteins, you can include all ten essential amino acids in your diet.

If you eat more protein than needed for the synthesis of new proteins by cells, the excess is used for energy or stored as fat. One gram of protein provides four kilocalories of energy. This is the same amount of energy that one gram of carbohydrate provides.

Lipids

Lipids, or fatty acids, are organic compounds that consist of repeating units of carbon, hydrogen, and oxygen. They provide the body with energy. The heart and skeletal muscles rely mainly on lipids for fuel. One gram of lipids provides nine kilocalories of energy, more than twice the amount provided by carbohydrates or proteins. Lipids have several other functions as well. Lipids form an insulating sheath around nerve cells that helps nerve messages travel more quickly. Lipids also help form substances that regulate blood pressure, blood clotting, and blood lipid levels. In addition, lipids make up the membranes that surround cells.

The term fat is often used interchangeably with the term lipid, but fats are actually a particular type of lipid, called **triglycerides**, in which three fatty acids are bound to a compound called glycerol. Fats are important in the body. They are the main form in which the body stores energy. Stored body fat is called adipose tissue. Stored fat not only provides an energy reserve but also cushions and protects internal organs. In addition, stored fat insulates the body and helps prevent heat loss in cold weather.

Although lipids and fats are necessary for life, they may be harmful if they are present in the blood at high levels. Both triglycerides and the lipid called cholesterol are known to damage blood vessels if their concentrations in the blood are too high. By damaging blood vessels, triglycerides and cholesterol also increase the risk of heart disease.

Lipids are classified as either saturated fatty acids or unsaturated fatty acids. This classification is based on the number of chemical bonds between carbon atoms in lipid molecules.

- **Saturated fatty acids** have only single bonds between carbon atoms. This gives them properties that make them unhealthful. Their amount in the diet should be kept as low as possible. If consumed in excess, they contribute to high blood levels of cholesterol and triglycerides. Saturated fatty acids are found in animal foods, such as meat, whole milk, and eggs.
- **Unsaturated fatty acids** have at least one double bond between carbon atoms. This gives them properties that make them more healthful. Eaten in appropriate amounts, they may help lower blood levels of cholesterol and triglycerides and decrease the risk of cardiovascular disease. They are found mainly in plant foods.

The human body can synthesize all but two of the fatty acids it needs: omega-3 fatty acids and omega-6 fatty acids. Both are unsaturated fatty acids. They are called essential fatty acids because they must be present in the diet. They are found in salmon, vegetable oil, flaxseed, eggs, and whole grains. Small amounts of these two fatty acids may help lower blood pressure as well as blood levels of harmful lipids.

Unsaturated fatty acids known as trans fatty acids (or trans fats), are manufactured from plant oils and do not occur naturally. They are added to foods to extend their shelf life.

Trans fats have properties like saturated fats and may increase risk of cardiovascular disease. They should be avoided in balanced eating. Many manufacturers no longer add trans fats to food products, and their use in restaurants has been banned in some cities.

Water

You may not think of water as a food, but it is a nutrient. Water is essential to life because it is the substance within which all the chemical reactions of life take place. An adult can survive only a few days without water. **Table 1**, above, shows water requirements for young people.

Water is lost from the body in exhaled air, sweat, and urine. Dehydration occurs when a person does not take in enough water to replace the water that is lost. Symptoms of dehydration include headaches, low blood pressure, and dizziness. If dehydration continues, it can quickly lead to unconsciousness and even death. When you are very active, particularly in the heat, you can lose a great deal of water in sweat. To avoid dehydration, you should drink extra fluids before, during, and after exercise.

Taking in too much water—especially without consuming extra salts—can lead to a condition called hyponatremia. In this condition, the brain swells with water, causing symptoms such as nausea, vomiting, headache, and coma. Hyponatremia can be fatal, so it requires emergency medical care.

Balanced Eating

Balanced eating is a way of eating that promotes good health. It includes eating several medium-sized meals regularly throughout the day. It also includes eating the right balance of different foods to provide the body with all the nutrients it needs. **Table 1**, above, lists macronutrient needs for young people, and you just read about foods that provide each of these macronutrients. How much of these foods should you eat to get the right balance of nutrients? Two tools for choosing foods that provide balanced nutrition are MyPyramid and nutrition labels on food packages.

MyPyramid

MyPyramid was developed by the U.S. Food and Drug Administration. It shows how much you should eat each day of foods in different food groups. MyPyramid is shown in **Figure** 23.1. You can visit the MyPyramid.gov website for more details or to customize MyPyramid for your gender, age, activity level, and other factors.

Figure 23.1: MyPyramid is visual representation of how much you should eat each day of foods in different food groups.

Guidelines for Using MyPyramid

1. The six colored bands represent six food groups:

- Brown = Grains—At least half should be whole grains.
- Green = Vegetables—Choose a variety of vegetables, including dark green and orange vegetables, dry beans and peas.
- Red = Fruits—Include a variety of fruits, and consume whole fruits instead of fruit juices.
- Yellow = Oils—Choose mainly unsaturated nut and vegetable oils.
- Blue = Milk—Dairy products should be low-fat or fat-free choices.
- Purple = Meat and Beans—Choose fish and low-fat meats, as well as beans, peas, nuts, and seeds.

2. The width of each colored band shows the proportion of food that should come from each food group.

3. The figure climbing stairs reminds you to balance food with exercise: 30–60 min/day of moderate-to-vigorous activity is recommended for most people.

Each food group represented by a colored band in MyPyramid is a good source of nutrients. The wider the band, the more you should eat from that food group. For example, the brown band is widest, so the largest proportion of foods should come from the grains group. The

white tip of MyPyramid represents foods that should be eaten only in very small amounts or very infrequently. They include foods such as ice cream and potato chips that contain few nutrients and may contribute excess kilocalories to the diet.

The figure "walking" up the side of MyPyramid in **Figure** 23.1 represents the role of exercise in balanced eating. Daily exercise helps you burn any extra energy that you consume in foods. The more active you are, the more energy you use. Light activities, such as golfing, typically use only a few hundred kilocalories per hour. Strenuous activities, such as running, may use over 900 kilocalories per hour.

Harvard University recently developed an alternative healthy eating pyramid, which is shown in **Figure** 23.2. It differs from MyPyramid in placing more emphasis on exercise and a greater focus on eating fruits, vegetables, and healthy plant oils. It moves red meats and starchy, low-nutrient foods, such as white bread and white rice, to the category of foods to eat in very limited amounts. Some experts think that the Harvard pyramid is less confusing than MyPyramid and represents an even healthier way of eating.

Food Labels

Packaged foods are required by law to carry a nutrition facts label, like the one in **Figure** 23.3, showing the nutrient content and ingredients in the food.

Reading nutrition facts labels can help you choose foods that are high in nutrients such as protein and low in nutrients such as fat. Nutrition facts labels can also help you choose foods that are nutrient dense. Nutrient density is the ratio of nutrient content, measured in grams, to total energy content in kilocalories.

Table 23.2: **Consider the following two foods:**

Food A	**Food B**
Protein: 15 g	Protein: 10 g
Energy: 300 kcal	Energy: 120 kcal
Nutrient Density:	Nutrient Density:
15g/300 kcal = 0.05 g/kcal	10g/120 kcal = 0.08 g/kcal

In terms of protein, Food B is more nutrient dense than Food A, because it provides more protein per kilocalorie. Eating nutrient-dense foods helps you to get enough of each nutrient without taking in too many kilocalories.

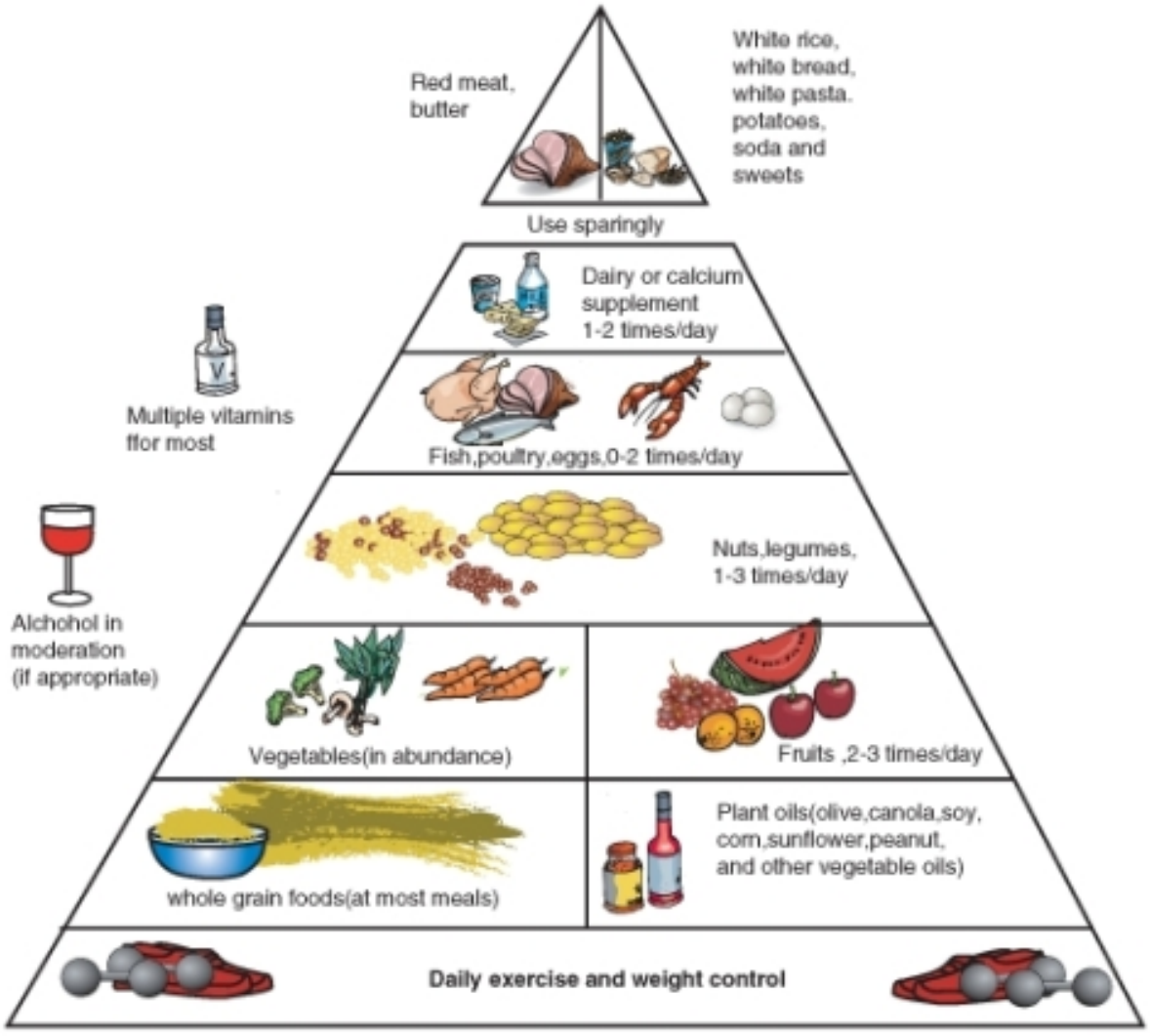
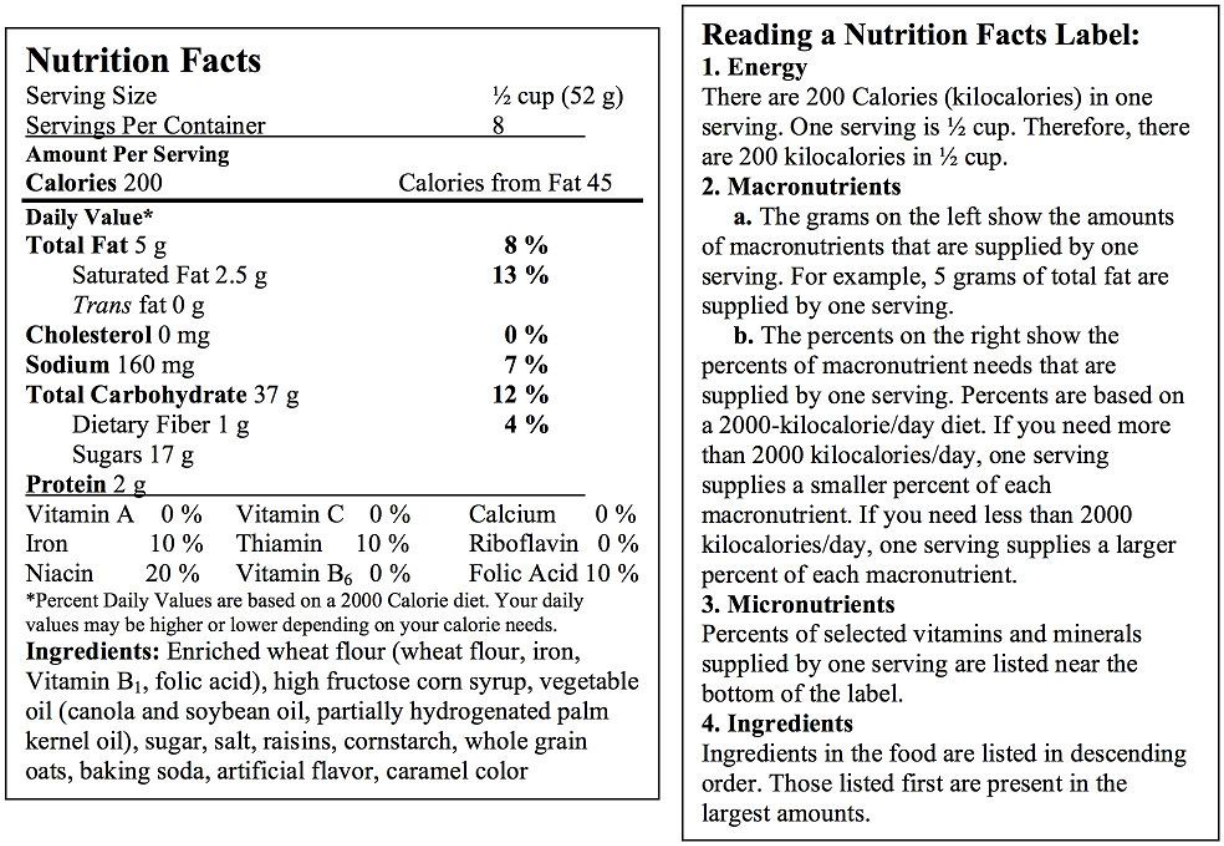


Figure 23.2: Healthy eating pyramid.



Nutrition Facts

Serving Size	½ cup (52 g)
Servings Per Container	8
Amount Per Serving	
Calories 200	Calories from Fat 45
Daily Value*	
Total Fat 5 g	**8 %**
Saturated Fat 2.5 g	**13 %**
Trans fat 0 g	
Cholesterol 0 mg	**0 %**
Sodium 160 mg	**7 %**
Total Carbohydrate 37 g	**12 %**
Dietary Fiber 1 g	**4 %**
Sugars 17 g	
Protein 2 g	

Vitamin A	0 %	Vitamin C	0 %	Calcium	0 %
Iron	10 %	Thiamin	10 %	Riboflavin	0 %
Niacin	20 %	Vitamin B_6	0 %	Folic Acid	10 %

*Percent Daily Values are based on a 2000 Calorie diet. Your daily values may be higher or lower depending on your calorie needs.

Ingredients: Enriched wheat flour (wheat flour, iron, Vitamin B_1, folic acid), high fructose corn syrup, vegetable oil (canola and soybean oil, partially hydrogenated palm kernel oil), sugar, salt, raisins, cornstarch, whole grain oats, baking soda, artificial flavor, caramel color

Reading a Nutrition Facts Label:

1. Energy

There are 200 Calories (kilocalories) in one serving. One serving is ½ cup. Therefore, there are 200 kilocalories in ½ cup.

2. Macronutrients

a. The grams on the left show the amounts of macronutrients that are supplied by one serving. For example, 5 grams of total fat are supplied by one serving.

b. The percents on the right show the percents of macronutrient needs that are supplied by one serving. Percents are based on a 2000-kilocalorie/day diet. If you need more than 2000 kilocalories/day, one serving supplies a smaller percent of each macronutrient. If you need less than 2000 kilocalories/day, one serving supplies a larger percent of each macronutrient.

3. Micronutrients

Percents of selected vitamins and minerals supplied by one serving are listed near the bottom of the label.

4. Ingredients

Ingredients in the food are listed in descending order. Those listed first are present in the largest amounts.

Figure 23.3: Nutrition facts label.

Reading the ingredients list on food labels can also help you choose healthful foods for balanced eating. At the top of the list, look for ingredients such as whole grains, vegetables, and fruits. These are foods you need the most of in a balanced diet. Avoid foods that contain processed ingredients, such as white flour or white rice. Processing removes nutrients. As a result, processed foods generally supply fewer nutrients than whole foods, even when they have been enriched or fortified with added nutrients.

Weight Gain and Obesity

Any unneeded energy in food, whether it comes from carbohydrates, proteins, or lipids, is stored in the body as fat. An extra 3,500 kilocalories of energy results in the storage of one pound (0.45 kg) of fat. People who consistently consume more food energy then they need gain weight. People who continue to store fat and gain weight may eventually become obese.

Obesity occurs when the body mass index is 30.0 kg/m_2 or greater. Body mass index (BMI) is a simple way to estimate the percentage of fat in the body. It is calculated by dividing an individual's weight (in kilograms) by the square of the individual's height (in meters). For example, a man who weighs 88 kilograms and is 1.7 meters tall has a BMI of:

$88 \text{ kg} \div (1.7 \text{ m})^2 = 30.4 \text{ kg/m}^2$.

Compare this BMI with the BMI values in **Table** 23.3. The man's BMI is greater than 29.9 kg/m^2, so he would be considered obese.

Table 23.3: **Body Mass Index and Weight Status**

BMI Value (kg/m^2)	Weight Status
<18.5	Underweight
18.5–24.9	Normal weight
25.0–29.9	Overweight
>29.9	Obese

People who are obese are at greater risk of many serious health problems, including metabolic syndrome. **Metabolic syndrome** is a cluster of conditions that together greatly increase the risk of cardiovascular disease. The conditions include type 2 diabetes, high blood pressure, and high blood levels of LDL cholesterol and triglycerides. A wide range of other disorders may also be related to obesity, including menstrual disorders in females, certain types of cancer, osteoarthritis, and depression. In addition, people who are obese have a lower life expectancy.

From 1980 to 2002, the number of obese adults in the U.S. doubled. By 2004, almost one-third of U.S. adults aged 20 years or older were obese. The prevalence of obesity in the U.S. is the highest in the developed world. Given its prevalence and serious health risks, obesity

is now a leading public health problem in this country.

The combination of eating too much and moving too little generally causes obesity. The best way to lose weight and avoid obesity is to eat less and exercise more. However, many factors may play a role in obesity, making it difficult for most people to eat wisely and lose weight. These factors may be genetic or environmental.

Several genes have been identified that control appetite and may contribute to some cases of obesity. An important environmental factor that contributes to obesity is the availability of high-fat, high-Calorie fast foods. Other environmental factors that may influence eating habits and contribute to obesity include stress, cultural traditions, and food advertisements. Some people who are obese have an eating disorder called binge eating. Eating disorders are discussed below.

Vitamins and Minerals

Unlike the major macronutrients, micronutrients—including vitamins and minerals—do not provide energy. Nonetheless, adequate amounts of micronutrients are essential for good health. The needed amounts generally can be met with balanced eating. However, many people do not eat enough of the right foods to meet their requirements. They may need vitamin or mineral supplements to increase their intake of micronutrients.

Vitamins

Vitamins are organic compounds that are needed by the body to function properly. There are 13 vitamins that humans need. They are described in **Table** 23.4, which also includes recommended daily vitamin intakes for teens.

Vitamins play many roles in good health, ranging from helping maintain vision to helping form red blood cells. Many vitamins are components of enzymes. For example, vitamin K is a component of enzymes involved in blood clotting. Several vitamins, including vitamins C and E, act as antioxidants. An antioxidant is a compound that neutralizes chemicals called free radicals. Free radicals are produced naturally during cellular activities and may cause some types of cancer. Neutralizing free radicals makes them harmless.

Some vitamins, including vitamin B_6, are produced by bacteria that normally live in the intestines, where they help digest food. Vitamin D is synthesized in the skin when it is exposed to UV radiation in sunlight. Most other vitamins must be obtained from foods because the body is unable to synthesize them. Good food sources of vitamins are listed in the table below. They include whole grains, vegetables, fruits, milk, and nuts.

Consuming inadequate amounts of vitamins can cause deficiency diseases. For example, consuming inadequate amounts of vitamin D causes soft bones. In children this is called rickets. It can cause permanent bone deformities. Consuming too much of some vitamins

can also be dangerous. Overdoses of vitamins can cause problems ranging from diarrhea to birth defects and even death.

Vitamins are either fat-soluble or water-soluble. This determines whether they can accumulate in the body and lead to overdoses.

- Vitamins A, D, E, and K are fat soluble. Excess intakes of these vitamins are stored in fatty tissues of the body. Because they are stored in the body, they can build up to toxic levels, especially if they are taken improperly in supplements.
- Vitamin C and all the B vitamins are water soluble. Excess amounts of these vitamins are excreted in the urine, so they are unlikely to reach toxic levels in the body.

Table 23.4: **Vitamins**

Vitamin (Chemical Name)	Functions in the Body	Good Food Sources	Recommended Daily Intakes f or Ages 14–18 yr
Vitamin A (Retinoids)	Needed for good vision, reproduction, and fetal development	Carrots, spinach, milk, eggs	Males: 900 g Females: 700 g
Vitamin B_1 (Thiamine)	Helps break down macronutrients; essential for proper functioning of nerves	Whole wheat, peas, beans, fish, peanuts, meats	Males: 1.2 mg Females: 1.0 mg
Vitamin B_2 (Riboflavin)	Helps the body process amino acids and fats; acts as antioxidant	Milk, liver, green leafy vegetables, almonds, soybeans	Males: 1.3 mg Females: 1.0 mg
Vitamin B_3 (Niacin)	Helps release energy from macronutrients; needed for healthy skin and nerves	Beets, beef liver, pork, turkey, fish, sunflower seeds, peanuts	Males: 16 mg Females: 14 mg
Vitamin B_5, (Pantothenic Acid)	Helps form critical enzymes for synthesis of macronutrients	Whole grains, legumes, eggs, meat	Males: 5 mg* Females: 5mg*

Table 23.4: (continued)

Vitamin (Chemical Name)	Functions in the Body	Good Food Sources	Recommended Daily Intakes f or Ages 14–18 yr
Vitamin B_6 (Pyridoxine)	Forms enzymes needed for amino acid synthesis and energy storage	Cereals, yeast, liver, fish, avocadoes, nuts, green beans	Males: 1.3 mg Females: 1.2 mg
Vitamin B_7 (Biotin)	Enables synthesis of fatty acids; helps store energy; keeps level of blood sugar stable	None	Males: 25 g* Females: 25 g*
Vitamin B_9 (Folate)	Needed to make red blood cells	Liver, green leafy vegetables, dried beans and peas	Males: 400 g Females: 400 g
Vitamin B_{12} (Cyanocobalamin)	Needed for normal functioning of nervous system and formation of blood	Meat, liver, milk, shellfish, eggs	Males: 2.4 g Females: 2.4 g
Vitamin C (Ascorbic Acid)	Needed to make many biological chemicals; acts as antioxidant	Citrus fruits such as oranges, red peppers, broccoli, kiwi	Males: 75 mg Females: 65 mg
Vitamin D (Ergocalciferol and Cholecalciferol)	Helps maintain blood levels of calcium; needed for healthy bones and teeth	Salmon, tuna, eggs, mushrooms	Males: 5 g Females: 5 g
Vitamin E (Tocopherol)	Acts as antioxidant; protects cell membranes from LDL cholesterol damage	Vegetable oils, nuts, green leafy vegetables, whole grains, fish	Males: 15 mg Females: 15 mg

Table 23.4: (continued)

Vitamin (Chemical Name)	Functions in the Body	Good Food Sources	Recommended Daily Intakes f or Ages 14–18 yr
Vitamin K (Naphthoquinone)	Helps transport calcium; helps blood clot	Kale, spinach, Brussels sprouts, milk, eggs, soy products	Males: 75 g* Females: 75 g*

- Recommended daily intakes not established; figures given are adequate daily intakes.

Minerals

Dietary minerals are chemical elements that are essential for body processes. Minerals are inorganic, meaning they do not contain carbon. Minerals needed by humans in relatively large amounts (greater than 200 mg/day) are listed in **Table** 23.5. Minerals not listed in the table are called trace minerals because they are needed in very small amounts. Trace minerals include chromium, iodine, iron, molybdenum, selenium, and zinc.

Table 23.5: **Minerals**

Mineral Name (Symbol)	Functions in the Body	Good Food Sources	Recommended Daily Intakes (mg) for Ages 14–18 yr
Calcium (Ca)	Needed for nerve and muscle action; builds bone and teeth; helps blood clot	Milk, soy milk, green leafy vegetables, sardines	Males: 1300* Females: 1300*
Chloride (Cl)	Helps maintain water and pH balance; helps form stomach acid	Table salt, most processed foods	Males: 2300* Females: 2300*
Magnesium (Mg)	Needed to form several enzymes	Whole grains, green leafy vegetables, nuts, seeds	Males: 410 Females: 360

Table 23.5: (continued)

Mineral Name (Symbol)	Functions in the Body	Good Food Sources	Recommended Daily Intakes (mg) for Ages 14–18 yr
Phosphorus (P)	Component of bones, teeth, lipids, and other important molecules in the body	Meat, poultry, whole grains	Males: 1250 Females: 1250
Potassium (K)	Needed for muscle and nerve function; helps maintain salt-water balance in body fluids	Meats, grains, orange juice, potatoes, bananas	Males: 4700* Females: 4700*
Sodium (Na)	Needed for muscle and nerve function; helps maintain salt-water balance in body fluids	Table salt, most processed foods	Males: 1500* Females: 1500*
Sulfur (S)	Necessary component of many proteins	Whole grains, meats, seafood, eggs	Males: 1300* Females: 1300*

- Recommended daily intakes not established; figures given are adequate daily intakes.

Minerals play many important roles in the body. Most are found in the blood and cytoplasm of cells, where they control basic functions. For example, calcium and potassium regulate nerve and muscle activity. Several minerals, including zinc, are components of enzymes. Other minerals, including calcium, form the bulk of teeth and bones.

Minerals cannot be synthesized by the body. Good food sources of minerals are listed in **Table** 23.5. They include dairy products, green leafy vegetables, and legumes. Mineral deficiencies are uncommon, but inadequate intakes of a few minerals may lead to health problems. For example, an inadequate intake of calcium may contribute to osteoporosis, a disease in which bones become brittle and break easily.

Some minerals may be toxic in excess, but overdoses of most minerals are uncommon. Overdoses are more likely when mineral supplements are taken. Salt (sodium chloride) is added to many foods, so the intake of sodium may be too high in many people. Too much sodium in the diet can cause high blood pressure in some individuals.

Other Micronutrients

Recently, new micronutrients called phytochemicals have been found in plants. They occur primarily in colorful fruits and vegetables, like those shown in **Figure** 23.4. Thousands of phytochemicals have been discovered, and some have already been shown to lower the risk of certain diseases. For example, the phytochemical lutein helps reduce the risk of macular degeneration, an eye disease that leads to blindness. Lutein is found in many yellow and orange fruits and vegetables. Several phytochemicals, including some found in berries, have proven to be powerful antioxidants.

Figure 23.4: Good sources of phytochemicals.

Eating Disorders

Eating disorders are psychiatric illnesses that involve abnormal patterns of eating. A person with an eating disorder has a compulsion to eat in a way that causes physical, mental, and emotional health problems. Typically, the person has an obsession with food and weight. Eating disorders are more common in females. One reason may be society's focus on female appearance. The most common eating disorders are binge eating disorder, anorexia nervosa, and bulimia nervosa.

Binge Eating Disorder

Binge eating disorder is characterized by compulsive overeating. People with the disorder typically eat very large quantities of food in a short period of time. They may use food as a way to deal with painful emotions or stress. Many people with the disorder are overweight or

obese. The disorder is rapidly increasing in prevalence and is now the most common eating disorder in the U.S. The rise in binge eating disorder is one reason for the dramatic increase in obesity in this country

Anorexia Nervosa

Anorexia nervosa is characterized by greatly restricted food intake and low body weight (BMI less than 17.5 kg/m^2). People with anorexia nervosa usually have a distorted body image. They think they are too fat when they are actually too thin. They have an obsessive fear of gaining weight and voluntarily starve themselves. They may also exercise excessively to help keep their weight low. Females with anorexia nervosa usually stop having menstrual periods. The disorder mainly affects teenage girls and is extremely serious. At least 10 percent of people with anorexia nervosa die from factors related to the disorder.

Bulimia Nervosa

Bulimia nervosa is characterized by cycles of binge eating followed by purging to eliminate the food from the body. Purging may be achieved through intentional vomiting or excessive use of laxatives. People with this disorder typically have normal weight or weight slightly greater than normal. Repeated purging can lead to dehydration. Excessive vomiting can damage the teeth and organs of the digestive system. Bulimia nervosa occurs most often in teenage girls and young women.

Causes and Treatment

People with eating disorders usually have other mental health problems as well, most commonly depression. Both depression and eating disorders may have the same underlying physiological cause: low levels of the brain chemical serotonin. The process of eating causes serotonin to be released and may lead to a temporary "high." The process of purging may also have this effect in people with bulimia nervosa.

Environmental factors play a role in most cases of eating disorders, as they do with depression and other mental health problems. Childhood abuse may be one of these environmental factors. Many people with eating disorders report having been abused as children.

Eating disorders can be treated with psychiatric therapy or psychological counseling. Medications may also be prescribed. Treatment usually includes resolving underlying emotional problems, as well as treating depression or other mental health disorders that are also present. In patients with anorexia nervosa, weight gain is also an important goal of treatment.

Lesson Summary

- Macronutrients include carbohydrates, proteins, and lipids. They are needed in relatively large amounts to supply the body with energy and building materials.
- Balanced eating can provide the body with the nutrients it needs without causing weight gain. Balanced eating includes eating a wide variety of healthful foods.
- Vitamins and minerals are micronutrients. They are needed in relatively small amounts to control many body processes.
- Eating disorders are serious but treatable psychiatric illnesses. They involve abnormal eating patterns and an obsession with food and weight.

Review Questions

1. Which classes of nutrients provide the body with energy?
2. How is obesity diagnosed?
3. Identify the two main classes of micronutrients and give an example of each.
4. What is an eating disorder?
5. If Jera is a 15-year-old female, how many grams of carbohydrates and proteins should she eat each day?
6. How can MyPyramid help you have a balanced diet?
7. Why is it more dangerous to consume too much of a fat-soluble vitamin than a water-soluble vitamin?
8. Compare and contrast anorexia nervosa and bulimia nervosa.

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Vocabulary

anorexia nervosa Eating disorder characterized by greatly restricted food intake and low body weight.

bulimia nervosa Eating disorder characterized by cycles of binge eating followed by purging to eliminate the food from the body.

binge eating disorder Eating disorder characterized by compulsive overeating. People with the disorder typically eat very large quantities of food in a short period of time.

carbohydrates Organic (or carbon-containing) compounds consisting of the elements carbon, hydrogen, and oxygen; provides the body with energy.

complete proteins Contain all ten essential amino acids; found in animal foods such as milk and meat.

eating disorder Psychiatric illnesses that involve abnormal patterns of eating.

essential amino acids Amino acids that cannot be synthesized and must be obtained from the diet.

hyponatremia A condition in which the brain swells with water, causing symptoms such as nausea, vomiting, headache, and coma.

incomplete proteins Proteins that are missing one or more essential amino acids; found in plant foods such as legumes and rice.

lipids (fatty acids) Organic compounds that consist of repeating units of carbon, hydrogen, and oxygen; provide the body with energy.

macronutrients Nutrients that the body needs in relatively large amounts; include carbohydrates, proteins, lipids, and water.

metabolic syndrome A cluster of conditions that together greatly increase the risk of cardiovascular disease; include type 2 diabetes, high blood pressure, and high blood levels of LDL cholesterol and triglycerides.

micronutrients Nutrients the body needs in relatively small amounts; include vitamins and minerals.

minerals Inorganic chemical elements that are essential for body processes.

MyPyramid A visual representation of how much you should eat each day of foods in different food groups.

nutrients Chemical elements or compounds that the body needs for normal functioning and good health.

obesity Occurs when the body mass index is 30.0 kg/m_2 or greater.

proteins Relatively large organic compounds containing carbon, hydrogen, oxygen, and nitrogen; made of amino acids.

saturated fatty acids Fatty acids with only single bonds between carbon atoms.

triglyceride Fat; a particular type of lipid in which three fatty acids are bound to a compound called glycerol.

unsaturated fatty acids Fatty acids with at least one double bond between carbon atoms.

vitamins Organic compounds that are needed by the body to function properly. There are 13 vitamins that humans need.

Points to Consider

- You need nutrients for energy and building materials. Balanced eating provides you with foods that contain the nutrients you need. How does your body obtain the nutrients from food?
- What processes break down food and make nutrients available to the body? What organs carry out the processes?

23.2 Lesson 23.2: Digestive System

Lesson Objectives

- Describe the organs and major functions of the digestive system.
- Explain how the mouth, esophagus, and stomach start the digestion of food.
- Explain how the small intestine completes digestion and absorbs nutrients.
- State the functions of the large intestine and the roles of intestinal bacteria.
- Identify and describe diseases of the digestive system.

Introduction

Suppose you are studying and having trouble concentrating. You decide to eat an apple for energy. How does energy stored in the apple get into your cells? What organs and processes break down the apple into nutrients that the body can use for fuel? What organs and processes let the nutrients enter your bloodstream so they can travel to the cells where they are needed? The basic processes involved are digestion and absorption. The organs involved are the organs of the digestive system.

Organs and Functions of the Digestive System

Organs that make up the digestive system are shown in **Figure** 23.5. Most of the organs form the gastrointestinal tract. Other digestive organs are called accessory organs. As you read about the organs below, refer to **Figure** 23.5 for reference.

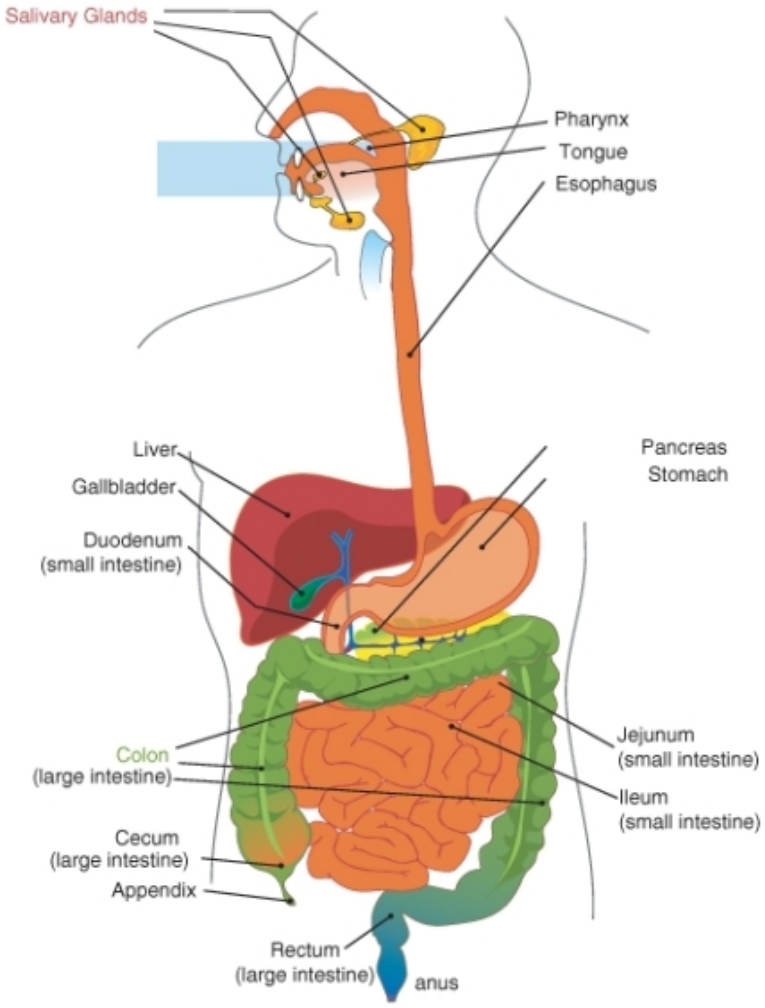

Figure 23.5: Organs of the digestive system.

Gastrointestinal Tract

The gastrointestinal (GI) tract is a long tube that connects the mouth with the anus. It is more than 9 meters long in adults. The GI tract can be divided into an upper and lower part. The upper GI tract includes the mouth, esophagus, and stomach. The lower GI tract

includes the small and large intestines. Food enters the mouth, passes through the upper and lower GI tracts, and then exits the body as feces through the anus.

The organs of the GI tract are covered by two layers of muscles that enable peristalsis. Peristalsis is a rapid, involuntary, wave-like contraction of muscles. It pushes food through the GI tract. The inside of GI tract is lined with mucous membranes. Mucous membranes are moist tissues that can secrete and absorb substances. The ability to secrete and absorb substances is necessary for the functions of the digestive system. See http://en.wikipedia.org/wiki/File:Peristalsis.gif for an animation of peristalsis.

Accessory Organs of the Digestive System

In the lower GI tract, additional organs play important roles in digestion. They are called accessory organs. Food does not pass through them, but they make or store substances needed for digestion. The accessory organs are the liver, gall bladder, and pancreas.

- The liver is a large organ next to the stomach. It produces digestive substances that are carried by ducts, or tubes, to the small intestine and gall bladder.
- The gall bladder is a small, pear-shaped structure below the liver. It stores substances from the liver until they are needed by the small intestine.
- The pancreas is a gland below the stomach. It produces digestive substances that are carried by a duct to the small intestine.

The Liver

The liver is a vital organ that has many functions, including detoxification of blood, protein synthesis, and production of biochemicals necessary for digestion. The liver is also involved in glucose balance. The liver produces bile which breaks down lipids.

The liver performs several roles in carbohydrate metabolism, which help in the balance of blood glucose levels:

- Gluconeogenesis: the synthesis of glucose from certain amino acids, lactate or glycerol
- Glycogenolysis: the breakdown of glycogen into glucose
- Glycogenesis: the formation of glycogen from glucose.

The liver is one of the most important organs in the body when it comes to blood filtering and detoxification. The liver is involved in getting rid of foreign substances and toxins, especially from the gut. The toxins are usually excreted in bile or urine. Breaking down toxins is referred to as drug metabolism, and is usually done using specialized enzymes produced in the liver. Most of the blood being filtered by the liver is from the portal vein, which carries blood from the intestines. The liver can remove a broad range of microorganisms such as

bacteria, fungi, viruses and parasites from the blood. Infections and parasites can come from contaminated water and food, and then find their way into your gut and blood stream. Luckily the blood then goes to the liver for filtering.

The liver also performs several roles in lipid metabolism including cholesterol synthesis and the production of triglycerides (fats). The liver produces coagulation factors I (fibrinogen), II (prothrombin), V, VII, IX, X and XI, as well as protein C, protein S and antithrombin.

Functions of the Digestive System

The digestive system has three main functions: digestion of food, absorption of nutrients, and elimination of solid waste. Digestion is the process of breaking down food into components the body can absorb. There are two types of digestion: mechanical and chemical.

- Mechanical digestion is the physical breakdown of chunks of food into smaller pieces. It takes place mainly in the mouth and stomach.
- Chemical digestion is the chemical breakdown of large, complex food molecules into smaller, simpler nutrient molecules that can be absorbed by the blood. It takes place mainly in the small intestine.

Chemical digestion could not take place without the help of digestive enzymes. Enzymes are substances that speed up chemical reactions. Digestive enzymes speed up the reactions of chemical digestion. Digestive enzymes are secreted by glands in the mucous membranes of the mouth, stomach, small intestine, and pancreas. Different digestive enzymes help break down different types of food molecules, including carbohydrates, proteins, and lipids.

The name of a digestive enzyme typically ends with the suffix -*ase*, which means "enzyme". The rest of the name refers to the type of food molecules the enzyme helps digest. For example, the enzyme lipase helps digest lipid molecules, and the enzyme lactase helps digest molecules of the sugar lactose.

After food is digested, the resulting nutrients are absorbed. Absorption is the process in which substances pass into the blood stream, where they can circulate throughout the body. Absorption occurs mainly in the small intestine. Any remaining indigestible matter that cannot be absorbed passes into the large intestine as waste. The waste later passes out of the body through the anus in the process of elimination.

The Start of Digestion: The Mouth to the Stomach

The upper GI tract is the primary site of mechanical digestion. The chemical digestion of carbohydrates and proteins also begins in the upper GI tract.

The Mouth

The mouth is the first organ in the digestive tract, but digestion may start even before you put the first bite of food in your mouth. Why? The sight or aroma of an appetizing dish can stimulate the release of digestive enzymes by salivary glands inside your mouth. The major salivary enzyme is amylase. Once you start eating, amylase begins the chemical digestion of carbohydrates in the food. It helps break down complex starch molecules into simpler sugar molecules.

The mouth also plays an important role in mechanical digestion. The teeth help to digest food mechanically by breaking it into smaller pieces. Human teeth have different shapes and functions. As you can see in **Figure** 23.6, the incisors and canines at the front of the mouth are relatively thin and sharp. They shear and tear food when you bite into it. The premolars and molars at the back of the mouth are larger and broader. They grind food into smaller pieces as you chew.

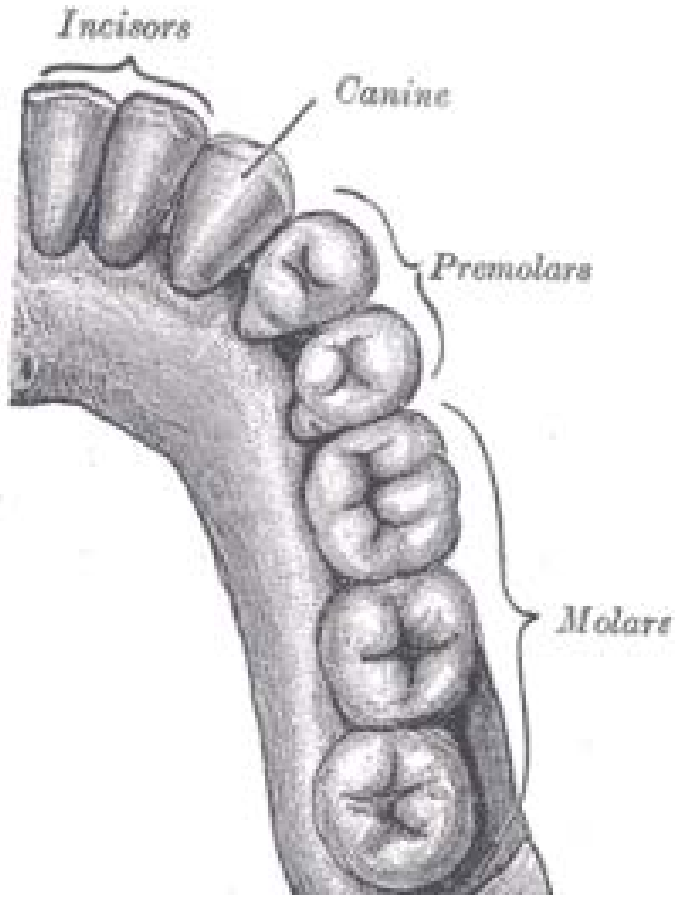

Figure 23.6: Types of human teeth.

Saliva from the salivary glands moistens the food and makes it easier to chew. The muscular

tongue helps mix the food with saliva and the enzymes it contains. When you swallow, the lump of chewed food, now called a bolus, passes into the pharynx.

The pharynx connects the mouth to the rest of the digestive tract. It also connects the mouth and nose to the rest of the respiratory system. As food is pushed to the back of the mouth by the tongue, it sets off an automatic response that closes the pharynx off from the respiratory system. This prevents you from accidentally inhaling food when you swallow.

Esophagus

From the pharynx, the bolus moves into the esophagus. The esophagus is a narrow tube about 20 centimeters long in adults. It begins at the pharynx, passes through the chest, and ends at the opening to the stomach. The function of the esophagus is to pass food from the mouth to the stomach. This takes only a few seconds. The esophagus does not produce digestive enzymes and does not have any other digestive functions.

Food moves through the esophagus due to peristalsis. At the end of the esophagus, a muscle called a sphincter controls the entrance to the stomach. The sphincter opens to let food into the stomach and then closes again to prevent the food from passing back into the esophagus.

Stomach

The stomach is a saclike organ located between the end of the esophagus and the beginning of the small intestine. In the stomach, food is further digested both mechanically and chemically. Churning movements of the stomach's thick muscular walls break down food mechanically. The churning movements also mix the food with fluids secreted by the stomach. These fluids include hydrochloric acid and digestive enzymes.

- Hydrochloric acid gives the stomach a very acidic environment. This helps destroy any bacteria that have entered the stomach in foods or beverages. An acidic environment is also needed for the stomach's digestive enzymes to work.
- Digestive enzymes secreted in the stomach help break down proteins into smaller molecules called peptides. The main digestive enzyme in the stomach is pepsin.

Water, alcohol, salt, and simple sugars can be absorbed through the lining of the stomach. Most other substances need further digestion in the small intestine before they can be absorbed. The stomach stores the food until the small intestine is ready to receive it. It may hold up to four liters of food when fully expanded. When the small intestine is empty, a sphincter opens between the stomach and small intestine. This allows the partially digested food, now called chyme, to enter the small intestine.

Digestion and Absorption: The Small Intestine

The small intestine is narrow tube about seven meters long in adults. It is the site of most chemical digestion and virtually all absorption. As you can see from Figure 1, the small intestine is much longer than the large intestine. It is called "small" because it is smaller in diameter than the large intestine. Like the rest of the GI tract, the small intestine pushes food along with peristalsis. The small intestine is made up of three parts: the duodenum, jejunum, and ileum. Each part has a different function.

Digestion in the Small Intestine

The **duodenum** is the first part of the small intestine. It is only about 25 cm long, but most chemical digestion occurs here. Many enzymes are active in the duodenum, and several are listed in **Table** 23.6. Some of the enzymes are produced by the duodenum. The rest are produced by the pancreas and secreted into the duodenum.

Table 23.6: **Digestive Enzymes Active in the Duodenum**

Name of Enzyme	Nutrient It Digests	Site of Production
Amylase	carbohydrates	pancreas
Trypsin	proteins	pancreas
Lipase	lipids	pancreas
Maltase	carbohydrates	small intestine
Peptidase	proteins	small intestine
Lipase	lipids	small intestine

How does the pancreas "know" when to secrete enzymes into the small intestine? The pancreas is controlled by compounds called hormones. Hormones are chemical messengers in the body. They regulate many body functions, including secretion of digestive enzymes. When food enters the stomach, a hormone called gastrin is secreted by the stomach. Gastrin, in turn, stimulates the pancreas to secrete its digestive enzymes.

The liver produces fluid called bile, which is secreted into the duodenum. Some bile goes to the gall bladder, where it is stored and becomes more concentrated. In the duodenum, bile breaks up large globules of lipids into smaller globules that are easier for lipase enzymes to break down chemically.

Bile also reduces the acidity of the chyme entering from the highly acidic stomach. This is important for digestion, because digestive enzymes in the duodenum require a neutral environment in order to work. The pancreas also contributes to the neutral environment of the duodenum by secreting bicarbonate, a basic substance that neutralizes acid.

Absorption in the Small Intestine

The **jejunum** is the second part of the small intestine. It is about 2.5 meters long. This is where most nutrients are absorbed into the blood.

As shown in **Figure** 23.7, the mucous membrane lining the jejunum is covered with microscopic, fingerlike projections called **villi** (singular: villus). Each villus, in turn, has thousands of even smaller projections called microvilli (singular: microvillus). The villi contain capillaries, which are tiny blood vessels. Nutrients are absorbed into these capillaries across the surface of the villi and microvilli. Because there are millions of these tiny projections, they greatly increase the surface area for absorption. In fact, villi and microvilli increase the absorptive surface of the small intestine to the size of a tennis court! This allows far greater absorption of nutrients.

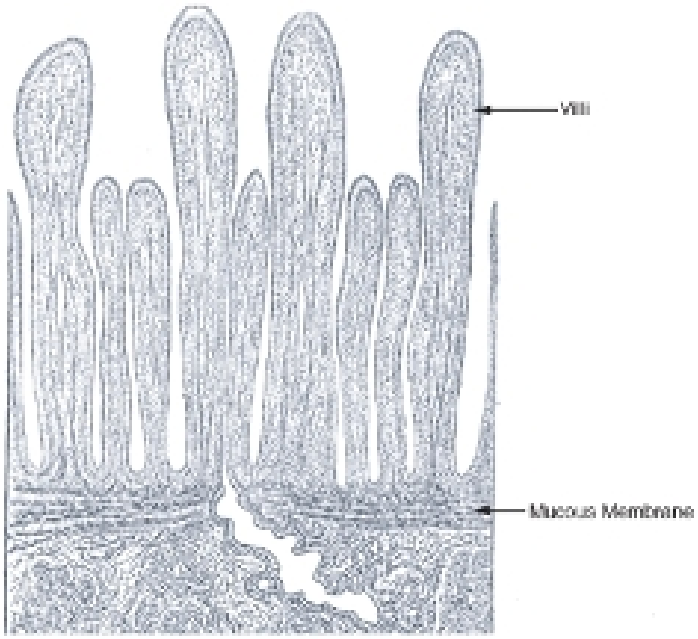

Figure 23.7: Magnified image of villi lining the jejunum (small intestine).

The **ileum** is the third part of the small intestine. It is about 3.5 meters long. A few remaining nutrients are absorbed in the ileum. Salts that form from liver bile are also absorbed there. Like the jejunum, the ileum is covered with villi and microvilli that increase the area for absorption.

The Large Intestine and Its Functions

From the small intestine, any remaining food waste passes into the large intestine. The large intestine is a relatively wide tube that connects the small intestine with the anus. It is about

1.5 meters long. The large intestine consists of three parts: the cecum, colon, and rectum.

Absorption of Water and Elimination of Wastes

The cecum is the first part of the large intestine, where waste enters from the small intestine. The waste is in a liquid state. As the waste passes through the colon, which is the second part of the large intestine, excess water is absorbed. After the excess water is absorbed, the remaining solid waste is called feces. Feces contain indigestible food substances such as fiber.

Feces accumulate in the rectum, which is the third part of the large intestine. As the rectum fills, the feces become compacted. The feces are stored in the rectum until they are eliminated from the body. A sphincter controls the anus and opens to let feces through to the outside. It normally takes from 12 to 24 hours for wastes to enter the cecum, move through colon, accumulate in the rectum, and pass from the body as feces.

Bacteria in the Large Intestine

Other functions of the large intestine are to provide a home for intestinal bacteria and to absorb the vitamins they produce. Trillions of bacteria normally live in the large intestine. Some of these bacteria are harmful to the body if they grow out of control. However, most of the bacteria are helpful. They produce several vitamins, including vitamins B_{12} and K. Intestinal bacteria play other helpful roles, as well. For example, they:

- control the growth of harmful bacteria.
- break down toxins before they can poison the body.
- break down indigestible food components.
- produce substances that help prevent colon cancer.

Diseases of the Digestive System

A number of diseases can affect the entire gastrointestinal tract. Other diseases affect particular organs of the GI tract. Still others affect accessory organs of the digestive system.

Diseases of the Gastrointestinal Tract

A group of diseases that affect the GI tract is called inflammatory bowel disease. Inflammatory bowel disease is inflammation of the large intestine and, in some cases, other parts of the GI tract. Inflammation is a normal reaction of the immune system to injury or infection that causes swelling, redness, and pain.

The two main forms of inflammatory bowel disease are Crohn's disease and ulcerative colitis. Both have similar symptoms, including abdominal pain, diarrhea, and weight loss. Crohn's disease is caused by the immune system reacting to the body's own tissues, but the cause of ulcerative colitis is not known. A tendency to develop the diseases may be inherited. Ulcerative colitis is confined to the colon and sometimes can be cured with surgery. Crohn's disease may occur anywhere in the GI tract and has no known cure, although treatment can control the symptoms.

Food allergies can also affect the entire GI tract. Food allergies are disorders that occur when the immune system reacts to substances in food as though they were harmful "foreign invaders." Foods that are most likely to cause allergies are nuts, eggs, milk, fish, and shellfish. Symptoms of food allergies may include tingling in the mouth, vomiting, and diarrhea. Food allergies can also cause skin rashes and difficulty breathing. An estimated eight percent of children and two percent of adults have food allergies.

Diseases of the Stomach and Esophagus

A layer of mucus normally protects the lining of the stomach from damage by hydrochloric acid. An infection by bacteria of the species *Helicobacter pylori* can weaken this mucus layer, allowing acid to get through to the delicate mucous membranes underneath. The acid may cause gastritis or stomach ulcers, both of which can be treated with medication.

- Gastritis is inflammation of the lining of the stomach. It causes abdominal pain.
- A stomach ulcer is a sore in the lining of the stomach. It causes severe abdominal pain and bleeding.

Stomach acid may also damage the lining of the esophagus. This can occur when the sphincter between the stomach and esophagus does not close properly. This lets acid from the stomach enter the esophagus. The acid may cause esophagitis, or inflammation of the esophagus. A common symptom of esophagitis is heartburn, which is a painful, burning sensation in the throat or chest. Esophagitis can be treated with medication and changes in diet. It is important to treat the condition because it sometimes leads to cancer of the esophagus if not treated.

Diseases of the Small Intestine

Diseases that affect the small intestine include ulcers, infections, and celiac disease. Ulcers of the small intestine occur mainly in the duodenum, because stomach acid enters the duodenum during digestion. If an infection by *Helicobacter pylori* weakens the mucous layer in the duodenum, the stomach acid can damage the mucous membranes underneath. Symptoms and treatment of duodenal ulcers are similar to those of stomach ulcers.

Other bacteria may also cause infections in the small intestine, including Salmonella and *E. coli*. The bacteria can enter the body in contaminated foods or beverages. Symptoms of bacterial infections include abdominal pain, cramping, vomiting, and diarrhea. Such infections typically clear up on their own without medical treatment.

Celiac disease is an immune reaction to a food protein called gluten, which is found in grains. A tendency to have celiac disease can be inherited. Symptoms of the disease include abdominal pain, diarrhea, and bloating. The symptoms can be prevented by eating a gluten-free diet, but there is no cure for the disease.

Diseases of the Large Intestine

Diseases that affect the large intestine include irritable bowel syndrome, colitis, and appendicitis. Irritable bowel syndrome (IBS) is a disorder in which the large intestine is easily irritated. It is one of the most common gastrointestinal disorders. The cause of IBS is unknown, but may be due to excessive bacteria in the intestine. Symptoms of the disorder include abdominal pain, cramping, constipation, and diarrhea. Symptoms can often be controlled with medication, stress management, and changes in diet. However, there is no cure for IBS.

Colitis is inflammation of the colon. It has many possible causes, ranging from bacterial infections to immune reactions against the body's own tissues. Symptoms of colitis include pain and tenderness in the abdomen. Treatment of colitis may include medication, surgery, and changes in diet.

Appendicitis is inflammation of the appendix. It is most common in children and teens. The appendix is a small, fingerlike pouch that extends from the cecum (see **Figure** 23.5). Inflammation of the appendix is usually caused by a bacterial infection. Symptoms include abdominal pain, loss of appetite, fever, and vomiting. Appendicitis is most often treated with surgery to remove the infected appendix. Without treatment, an infected appendix can be fatal.

Diseases of the Accessory Organs

Accessory organs of digestion can also be affected by disease, and this may interfere with normal digestion. A disease that affects the pancreas is cystic fibrosis. Cystic fibrosis (CF) is an inherited disease in which the body produces abnormally thick and sticky mucous. In the pancreas, the mucus blocks the duct to the duodenum, preventing pancreatic enzymes from reaching it. As a result, proteins and lipids cannot be digested properly. People with CF may take digestive enzymes by mouth to improve their digestion. However, the disease has no known cure. (For more information on CF, see chapter titled *Human Genetics.*)

Hepatitis is inflammation of the liver. It is usually caused by a viral infection. Several

different viruses can cause hepatitis. Some of the viruses spread through contaminated foods or beverages, others through sexual contact. Symptoms of hepatitis include fever, headache, vomiting, and abdominal pain. Another symptom is jaundice, which is yellowing of the skin and eyes. If the symptoms are mild, the disease may clear up without treatment. If the symptoms are more severe, the disease may damage the liver so it can no longer produce bile. This interferes with the digestion of lipids. Medications are available to treat hepatitis. Some types of hepatitis can also be prevented with vaccines.

Gall bladder problems occur mainly in adults. They are often caused by gall stones (**Figure** 23.8). Gall stones are crystals that form in the bile in the gall bladder. There are many possible reasons why gall stones form, including abnormal body chemistry and too much fat in the diet. Gall stones start out as small as a grain of sand but may grow to the size of a golf ball. There may be one large stone or many small ones. If gall stones block the duct that carries bile to the duodenum, they may cause inflammation of the gall bladder and severe abdominal pain. Generally, the only way to treat these problems is to surgically remove the gall stones or the entire gall bladder.

Figure 23.8: Gall stones.

Lesson Summary

- The digestive system includes the gastrointestinal tract and accessory organs such as the pancreas. The major functions of the digestive system are to digest food, absorb nutrients, and eliminate solid waste.
- Both mechanical and chemical digestion of food start in the mouth. The esophagus

carries the food to the stomach, and the stomach continues mechanical and chemical digestion.
- Most chemical digestion takes place in the small intestine with the help of several digestive enzymes. Virtually all absorption of nutrients also takes place in the small intestine.
- The large intestine removes excess water from waste and eliminates waste from the body. It also provides a home for helpful intestinal bacteria.
- Many diseases affect the digestive system and may interfere with digestion. They include food allergies, infections, and inherited conditions.

Review Questions

1. Name, in sequence, the digestive organs that food passes through in the gastrointestinal tract, from the mouth to the anus.
2. Describe two ways that the mouth helps digest food.
3. How do villi and microvilli help the small intestine absorb nutrients?
4. What are two functions of helpful bacteria in the large intestine?
5. Describe what happens to carbohydrates as they pass through the organs of the GI tract.
6. Antibiotics are medications that destroy bacteria. Explain how antibiotics might help treat stomach ulcers.
7. Why is it important for digestive system functions that mucous membranes can secrete and absorb substances?
8. Compare and contrast two digestive enzymes that work in the duodenum.

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Vocabulary

absorption The process in which substances pass into the blood stream, where they can circulate throughout the body; occurs mainly in the small intestine.

amylase The major salivary enzyme is amylase; begins the chemical digestion of carbohydrates in the food; helps break down complex starch molecules into simpler sugar molecules.

cecum The first part of the large intestine, where waste enters from the small intestine.

celiac disease An immune reaction to a food protein called gluten, which is found in grains.

chemical digestion The chemical breakdown of large, complex food molecules into smaller, simpler nutrient molecules that can be absorbed by the blood; takes place mainly in the small intestine.

colon The second part of the large intestine, where excess water is absorbed. After the excess water is absorbed, the remaining solid waste is called feces.

duodenum The first part of the small intestine; site where most chemical digestion occurs.

esophagus A narrow tube - begins at the pharynx, passes through the chest, and ends at the opening to the stomach. The function of the esophagus is to pass food from the mouth to the stomach.

gall bladder A small, pear-shaped structure below the liver; stores substances from the liver until they are needed by the small intestine.

gastritis Inflammation of the lining of the stomach.

gastrointestinal (GI) tract Organ of the digestive system; a long tube that connects the mouth with the anus.

ileum The third part of the small intestine. A few remaining nutrients are absorbed in the ileum, as are salts that form from liver bile.

inflammatory bowel disease Inflammation of the large intestine and, in some cases, other parts of the GI tract; includes Crohn's disease and ulcerative colitis.

irritable bowel syndrome (IBS) A disorder in which the large intestine is easily irritated.

jejunum The second part of the small intestine; where most nutrients are absorbed into the blood.

large intestine A relatively wide tube that connects the small intestine with the anus; consists of three parts: the cecum, colon, and rectum.

liver A large organ next to the stomach; produces digestive substances that are carried by ducts, or tubes, to the small intestine and gall bladder.

lower GI tract Segment of the GI tract that includes the small and large intestines.

mechanical digestion The physical breakdown of chunks of food into smaller pieces; takes place mainly in the mouth and stomach.

mucous membranes Moist tissues that can secrete and absorb substances.

pancreas A gland below the stomach; produces digestive substances that are carried by a duct to the small intestine.

peristalsis A rapid, involuntary, wave-like contraction of muscles; pushes food through the GI tract.

pharynx Connects the mouth to the rest of the digestive tract; also connects the mouth and nose to the rest of the respiratory system.

rectum The third part of the large intestine; where feces accumulates. As the rectum fills, the feces become compacted. The feces are stored in the rectum until they are eliminated from the body.

small intestine A narrow tube leading away from the stomach; made up of three parts: the duodenum, jejunum, and ileum; the site of most chemical digestion and virtually all absorption.

stomach A saclike organ located between the end of the esophagus and the beginning of the small intestine. In the stomach, food is further digested both mechanically and chemically.

stomach ulcer A sore in the lining of the stomach.

upper GI tract Segment of the GI tract that includes the mouth, esophagus, and stomach.

Points to Consider

- The large intestine eliminates the waste that remains after food is digested. More waste is produced when cells break down nutrients for energy and building materials. How is this waste removed from the body? Is it eliminated by the large intestine? Is it removed in some other way?

23.3 Lesson 23.3: Excretory System

Lesson Objectives

- Define homeostasis and excretion, and explain why they are necessary for life.
- Describe the urinary system, kidneys, and nephrons; summarize the processes involved in excretion.
- Identify roles of the kidneys in homeostasis.
- Name diseases of the urinary system, and explain how dialysis helps treat kidney failure.

Introduction

If you exercise on a hot day, you are likely to lose a lot of water in sweat. Then, for the next several hours, you may notice that you do not pass urine as often as normal and that your urine is darker than usual. Do you know why this happens? Your body is low on water and trying to reduce the amount of water lost in urine. How does the body know when it is low on water? How does it control the amount of water lost in urine? The answers to both questions are the kidneys and the glands that control them.

Homeostasis and Excretion

The kidneys are the body's main organs of homeostasis and excretion. Homeostasis is the body's attempt to maintain a constant internal environment. One of the major ways the body achieves homeostasis is through excretion. Excretion is the process of removing wastes and excess water from the body.

Homeostasis

Homeostasis is a fundamental characteristic of all living things. Internal body conditions must be kept within certain limits for the normal functioning of cells. Homeostasis involves keeping many internal factors at more or less constant levels. The factors include body

temperature and properties of the blood. For example, the blood must have certain levels of acidity, salts, and nutrients in order for cells to function normally.

A variety of homeostatic mechanisms help maintain stability of the internal environment. Each mechanism involves the interaction of at last three components: a receptor, a control center, and an effector.

- The receptor senses changes in the internal environment and sends the information to the control center.
- The control center processes the information, determines the appropriate action, and sends a command to the effector.
- The effector responds to the command and changes conditions in the internal environment.

An example of a homeostatic mechanism in humans is the regulation of body temperature. This is represented by the diagram in **Figure** 23.9. Temperature receptors in the skin send information about skin temperature to the brain. The brain is the control center. It determines whether the temperature is too high or too low and sends appropriate commands to effectors that control body temperature. Effectors include blood vessels near the surface of the body. If the temperature is too high, the brain commands the blood vessels to dilate, which helps the body lose heat. If the temperature is too low, the brain commands the blood vessels to constrict, which helps the body retain heat. These actions help return body temperature to normal.

Negative Feedback and Body Temperature

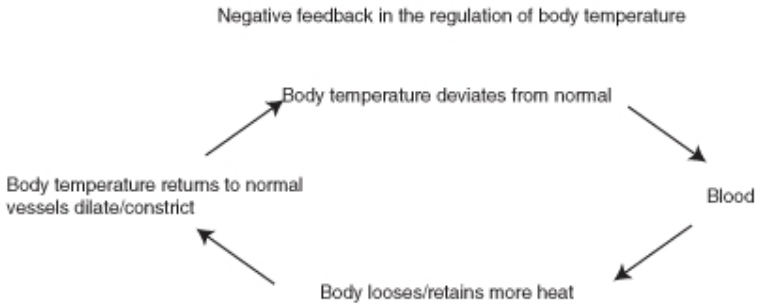

Figure 23.9: Regulation of body temperature is an example of negative feedback. When body temperature deviates from normal, this information feeds back to the brain and sets in motion changes that return body temperature to normal.

The regulation of body temperature is an example of negative feedback. Negative feedback is a type of homeostatic mechanism in which change in one direction results in a counteractive

change in the opposite direction. Negative feedback reverses the direction of change to bring conditions back to normal. Most of the mechanisms that control homeostasis in the human body involve negative feedback.

Positive feedback mechanisms also exist, but they are not common in the human body. Positive feedback accelerates or amplifies a change and pushes levels farther away from normal. One example of a positive feedback mechanism in the body is blood clotting, which is described in the chapter titled *Circulatory and Respiratory Systems*.

If homeostasis is disturbed, a homeostatic imbalance results. This may result in cells getting too much or not enough of certain substances. Many diseases are caused by homeostatic imbalances. For example, diabetes mellitus is a disease in which the blood contains too much glucose. This can have serious consequences for cells throughout the body. It may lead to damaged blood vessels, heart disease, blindness, and kidney failure.

Excretion

Excretion is an essential process in all forms of life. When cells metabolize—or break down—nutrients, waste products are produced. For example, when cells metabolize proteins and nucleic acids, nitrogen wastes such as ammonia, urea and uric acid are produced. Ammonia is a toxic substance and must be removed from the blood and excreted from the body. Urea is removed through urine, which is produced in the kidney. Excretion is also necessary to remove excess water, salts, and many other substances from the body.

Although the kidneys are the main organs of excretion of wastes from the blood, several other organs are also involved in excretion, including the large intestine, liver, skin, and lungs.

- The large intestine eliminates solid wastes that remain after the digestion of food in the gastrointestinal tract (as discussed in Lesson 23.2: Digestive System).
- The liver breaks down excess amino acids in the blood to form ammonia, and then converts the ammonia to urea, a less toxic substance. The liver also breaks down other toxic substances in the blood, including alcohol and drugs.
- The skin eliminates water and salts in sweat.
- The lungs exhale water vapor and carbon dioxide.

Kidneys and Excretion

The kidneys are part of the urinary system. The kidneys work together with other urinary system organs in the function of excretion. The urinary system is shown in **Figure** 23.10.

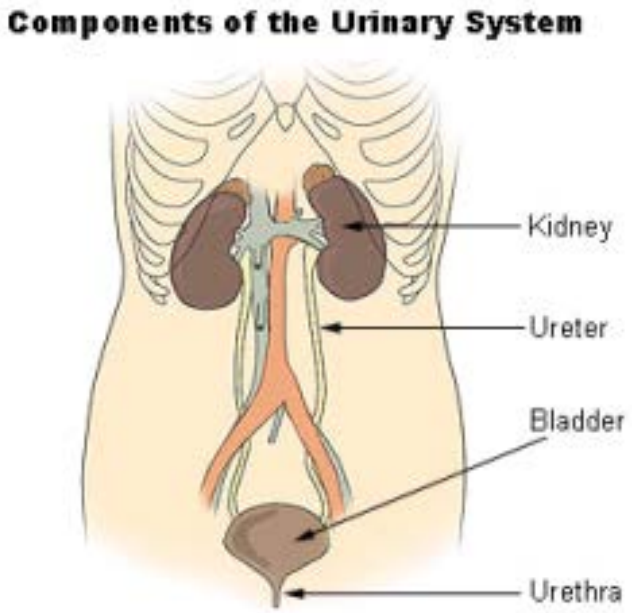

Figure 23.10: The urinary system.

Urinary System

In addition to the kidneys, the urinary system includes the ureters, bladder, and urethra. The main function of the urinary system is to filter waste products and excess water from the blood and remove them from the body. The two kidneys, which are described in detail below, filter the blood and form urine. Urine is the liquid waste product of the body that is excreted by the urinary system.

From the kidneys, urine enters the ureters, which carry it to the bladder. Each ureter is a muscular tube about 25 centimeters long. Peristaltic movements of the muscles of the ureter send urine to the bladder in small spurts.

The bladder is a hollow organ that stores urine. It can stretch to hold up to 500 milliliters. When the bladder is about half full, the stretching of the bladder sends a nerve impulse to the sphincter that controls the opening to the urethra. In response to the impulse, the sphincter relaxes and lets urine flow into the urethra.

The urethra is a muscular tube that carries urine out of the body. Urine leaves the body through another sphincter in the process of urination. This sphincter and the process of urination are normally under conscious control.

Kidneys

The kidneys participate in whole-body homeostasis. As mentioned above, one of the promary roles of the kidney is to remove nitrogenous wastes. The kidneys are a pair of bean-shaped, reddish brown organs about the size of a fist. They are located just above the waist at the back of the abdominal cavity, on either side of the spine. As shown in **Figure** 23.10, the kidneys are protected by the ribcage. They are also protected by a covering of tough connective tissues and two layers of fat, which help cushion them.

Located on top of each kidney is an adrenal gland, also shown in **Figure** 23.10. The two adrenal glands secrete several hormones. Hormones are chemical messengers in the body that regulate many body functions. The adrenal hormone aldosterone helps regulate kidney functions.

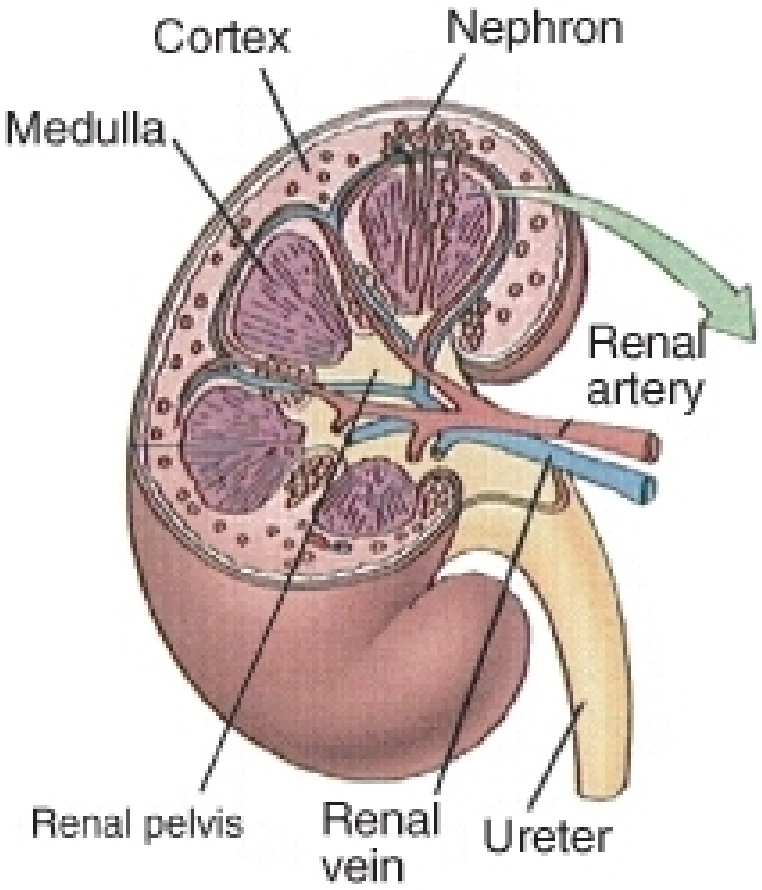

Figure 23.11: The human kidney.

In **Figure** 23.11, you can see that the kidney has three layers. The outer layer is the renal cortex, and the middle layer is the renal medulla. The inner layer, the renal pelvis, is where the renal artery enters the kidney and the renal vein exits the kidney. The renal artery

carries blood to the kidney to be filtered, and the renal vein carries the filtered blood away from the kidney. Structures in the kidney called nephrons are also seen in **Figure** 23.11. Each nephron extends from the cortex down into the medulla.

Nephrons

Nephrons are the structural and functional units of the kidneys. A single kidney may have more than a million nephrons. The diagram in **Figure** 23.12 represents an individual nephron and shows its main structures and functions. The structures include the glomerulus, Bowman's capsule, and renal tubule.

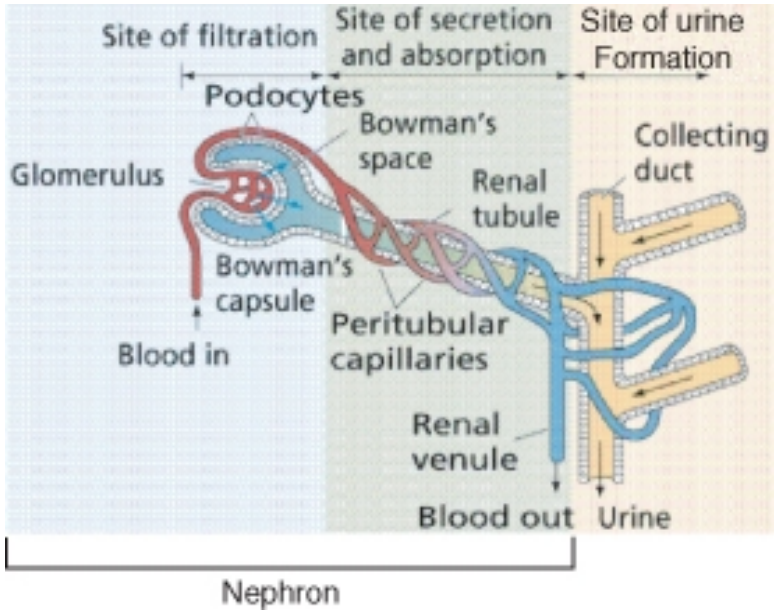

Figure 23.12: Nephron structures and functions.

- The glomerulus is a cluster of arteries that filters substances out of the blood.
- Bowman's capsule is a cup-shaped structure around the glomerulus that collects the filtered substances.
- The renal tubule is a long, narrow tube surrounded by capillaries that reabsorbs many of the filtered substances and secretes other substances.

Filtration, Reabsorption, and Secretion

The renal arteries, which carry blood into the kidneys, branch into the capillaries of the glomerulus of each nephron. The pressure of blood moving through these capillaries forces some of the water and dissolved substances in the blood through the capillary walls and into

Bowman's capsule. Bowman's capsule is composed of layers. The space between the layers, called Bowman's space, fills with the filtered substances.

The process of filtering substances from blood in the glomerulus is called filtration. The fluid that collects in Bowman's space is called filtrate. It is composed of water, salts, glucose, amino acids, and urea. Larger structures in the blood—including protein molecules, blood cells, and platelets—do not pass into Bowman's space. Instead, they return to the main circulation.

From Bowman's space, the filtrate passes into the renal tubule. The main function of the renal tubule is reabsorption. Reabsorption is the return of needed substances in the filtrate back to the bloodstream. It is necessary because some of the substances removed from the blood by filtration—including water, salts, glucose, and amino acids—are needed by the body. About 75 percent of these substances are reabsorbed in the renal tubule.

As shown in **Figure** 23.13, the renal tubule is divided into three parts: the proximal tubule, the Loop of Henle, and the distal tubule.

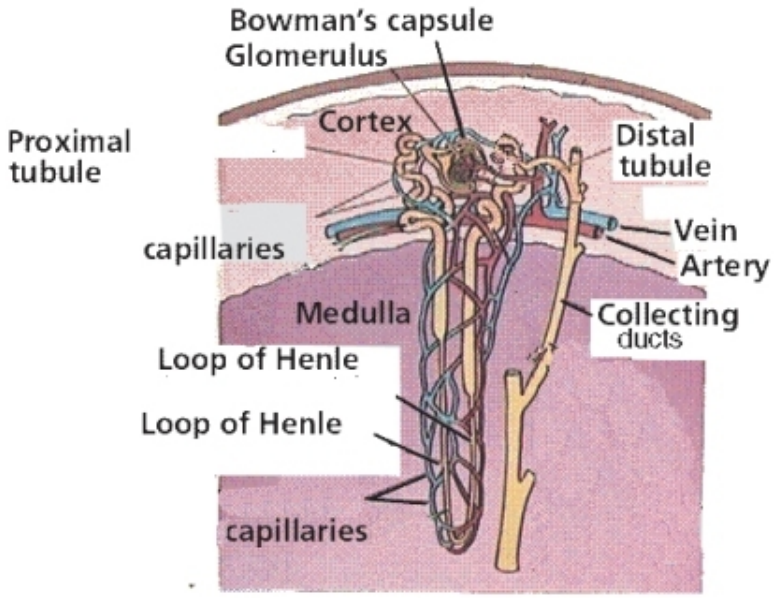

Figure 23.13: Parts of the renal tubule and other nephron structures.

- Filtrate first enters the proximal tubule. This is where that most reabsorption takes place. Tiny projections called microvilli line the proximal tubule and increase the surface area for reabsorption. From the proximal tubule, the filtrate passes through the loop of Henle.
- The loop of Henle carries the filtrate from the cortex down into the medulla and then back up to the cortex again. Its primary purpose is to reabsorb water and salt from the fluid. The remaining fluid enters the distal tubule.

- The distal tubule carries the fluid, now called tubular fluid, from the loop of Henle to a collecting duct. As it transports the fluid, the distal tubule also reabsorbs or secretes substances such as calcium and sodium. The process of secreting substances into the tubular fluid is called secretion.

Urine Formation

The collecting ducts are the site of urine formation. This process is crucial for water conservation in the body. The collecting ducts reabsorb water from tubular fluid and return it to the blood. The remaining fluid, called urine, has a smaller volume and a greater concentration than tubular fluid. From the collecting ducts, urine enters a ureter and is eventually excreted from the body.

The reabsorption of water by the collecting ducts is controlled by a negative feedback mechanism. The mechanism involves a hormone secreted by the pituitary gland, called antidiuretic hormone (ADH). ADH makes the collecting ducts more permeable to water, allowing more water to be reabsorbed from tubular fluid. When there is not enough water in the blood, more ADH is secreted, more water is reabsorbed from tubular fluid, and less water is excreted in urine. The opposite happens when there is too much water in the blood.

Kidneys and Homeostasis

The kidneys play many vital roles in homeostasis. As you have already read, the kidneys filter blood and excrete liquid waste. In fact, the kidneys filter all the blood in the body about 16 times a day, producing approximately 180 liters of filtrate and about 1.5 liters of urine. The kidneys also control the amount of water in the blood by excreting more or less water in urine.

Balancing the Blood

The kidneys are responsible for maintaining balance in the blood in other ways, as well. For example, they control the acid-base balance in the blood, mainly by secreting hydrogen ions into tubular fluid and reabsorbing bicarbonate ions from tubular fluid as needed. The kidneys also regulate blood concentrations of many other ions—including sodium, potassium, calcium, and magnesium—by the controlling the amounts that are excreted in urine.

Secreting Hormones

The kidneys also secrete various hormones to help maintain homeostasis. Hormones secreted by the kidneys include erythropoietin and rennin.

- Erythropoietin is secreted when the blood does not have enough red blood cells to carry adequate oxygen. The hormone stimulates the production of red blood cells by the bone marrow.
- Rennin is secreted when blood pressure falls. The hormone stimulates the secretion of aldosterone by the adrenal gland. Aldosterone, in turn, stimulates the kidneys to reabsorb more sodium ions and water. This increases the volume of the blood, which causes an increase in blood pressure.

Kidney Disease and Dialysis

A person can live a normal, healthy life with just one kidney. However, at least one kidney must function properly to maintain life. Diseases that threaten the health and functioning of the kidneys include kidney stones, infections, and diabetes.

Kidney Stones

Kidney stones are crystals of dissolved minerals that form in urine inside the kidneys. They may start out as small as a grain of salt and grow to be as large as a grapefruit. There may be one large stone or many small ones. Small kidney stones often pass undetected through the urinary tract and out of the body in urine. However, kidney stones may grow large enough before passing to block a ureter. This can cause a buildup of urine above the blockage and severe pain. Large kidney stones can sometimes be broken into smaller pieces that wash out of the urinary tract in urine. The stones are shattered by high-intensity sound waves focused on them from outside the body. Another alternative is to remove kidney stones surgically.

Infections

Bacterial infections of the urinary tract are very common. In fact, urinary tract infections (UTI) are the second most common type of bacterial infections seen by health care providers. Typical organisms that cause UTIs include *Escherichia coli* and *Staphylococcus saprophyticus*. The organisms may infect any part of the urinary tract.

The most common type of UTIs are bladder infections. They can be treated with antibiotics prescribed by a doctor. However, if a bladder infection is not treated, it may spread to the kidney and cause a kidney infection, or pyelonephritis. This is the most serious type of UTI. It can damage the kidney and interfere with normal kidney function. Kidney infections can also be treated with antibiotics but may require other treatments as well.

Diabetes

Two different types of diabetes can involve the kidneys: diabetes insipidus and diabetes mellitus. Diabetes insipidus is a disease characterized by the inability to concentrate urine. A person with this disease typically produces many liters of very dilute urine each day. Diabetes insipidus can be caused by a deficiency of ADH (antidiuretic hormone) or by the kidneys failing to respond to ADH. If the cause of diabetes insipidus can be treated, it may cure the disease.

In diabetes mellitus, the kidneys try to reduce the high glucose level in the blood by excreting more glucose in urine. This causes frequent urination and increased thirst. If blood glucose levels are not controlled by medication or diet, they may damage capillaries of the glomerulus and interfere with the kidney's ability to filter blood. Eventually, high glucose levels may lead to kidney failure, in which kidney function is greatly reduced. Kidney failure leads to high levels of urea and other wastes in the blood and may require treatment with dialysis.

Dialysis and Transplantation

Dialysis is a medical procedure in which blood is filtered with the help of a machine. One type of dialysis treatment is shown in **Figure** 23.14. Blood from the patient's vein enters the dialysis machine through a tube. Inside the machine, excess water, wastes, and other unneeded substances are filtered from the blood. The filtered blood is then returned to the patient's vein through another tube. A dialysis treatment usually lasts three to four hours and must be repeated three times a week. Dialysis is generally performed on patients who have kidney failure. Dialysis helps them stay alive, but does not cure their failing kidneys.

The only cure for most people with kidney failure is a kidney transplant. To be suitable for transplantation, the donated kidney must come from a donor who has the same blood and tissue types as the recipient. Even then, the recipient must take medication to suppress the immune system so it does not reject the new kidney.

Lesson Summary

- Homeostasis is the body's attempt to maintain a constant internal environment. Excretion helps achieve homeostasis by removing wastes, excess water, and other unneeded substances from the body. Both processes are essential for life.
- The urinary system includes the kidneys and other structures that excrete liquid waste. The kidneys are the main organs of excretion of wastes in the blood, and nephrons are structural and functional units of the kidneys. The kidneys filter blood, reabsorb and secrete substances, and form urine.
- The kidneys are the main organs of homeostasis. In addition to excretion, they regulate acid-base balance and ion concentrations in the blood. They also secrete hormones that

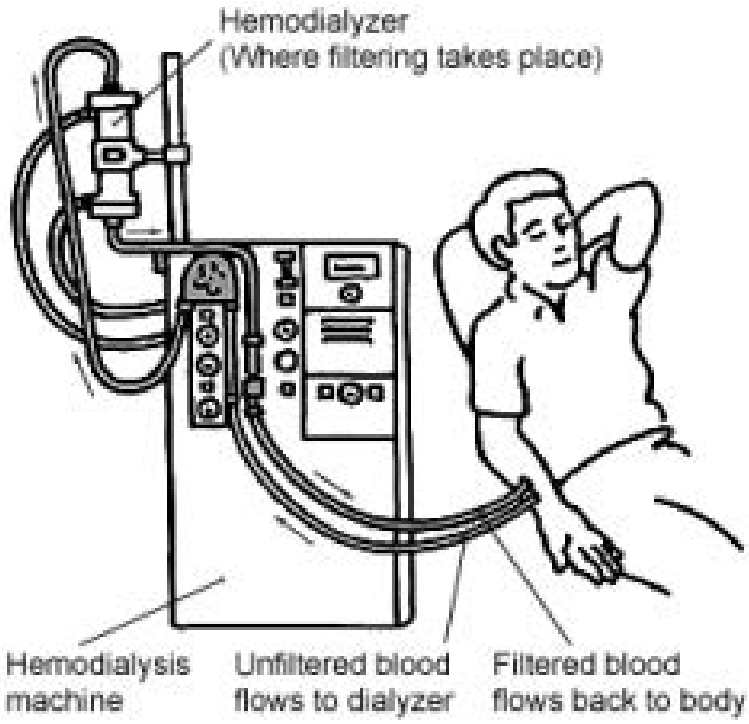

Figure 23.14: Patient receiving dialysis treatment.

control other body processes.
- Diseases of the urinary system include kidney stones, infections, and diabetes, which may lead to kidney failure. Kidney failure can be treated with dialysis, in which a machine filters the blood.

Review Questions

1. What are homeostasis and excretion?
2. Identify three organs of excretion and one substance that each organ excretes.
3. Why do the kidneys reabsorb some of the substances they filter from the blood?
4. Describe how urine forms in the collecting ducts of the kidneys.
5. How does ADH control the amount of water in urine? How is this an example of negative feedback?
6. Does an otherwise healthy person with just one kidney need dialysis? Why or why not?
7. Summarize the processes and structures involved in excretion by the kidneys.
8. Contrast the effects on the kidneys of diabetes insipidus and diabetes mellitus.

Further Reading / Supplemental Links

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- http://en.wikipedia.org

Vocabulary

bladder A hollow organ that stores urine.

Bowman's capsule A cup-shaped structure around the glomerulus that collects the fil-

tered substances; part of the nephron.

control center Involved in maintaining homeostasis; processes the information, determines the appropriate action, and sends a command to the effector.

dialysis A medical procedure in which blood is filtered with the help of a machine.

effector Involved in maintaining homeostasis; responds to the command and changes conditions in the internal environment.

erythropoietin Hormone secreted by the kidney when the blood does not have enough red blood cells to carry adequate oxygen; stimulates the production of red blood cells by the bone marrow.

excretion The process of removing wastes and excess water from the body.

filtration The process of filtering substances from blood in the glomerulus.

glomerulus Part of the nephron; a cluster of arteries that filters substances out of the blood.

homeostasis The body's attempt to maintain a constant internal environment.

kidney Organ that filters the blood and forms urine.

kidney stones Crystals of dissolved minerals that form in urine inside the kidneys.

loop of Henle Carries the filtrate from the cortex down into the medulla and then back up to the cortex again; primary purpose is to reabsorb water and salt from the fluid.

negative feedback A type of homeostatic mechanism in which change in one direction results in a counteractive change in the opposite direction; reverses the direction of change to bring conditions back to normal.

nephrons The structural and functional units of the kidneys; includes the glomerulus, Bowman's capsule, and renal tubule.

positive feedback Accelerates or amplifies a change and pushes levels farther away from normal; not common in the human body.

reabsorption The return of needed substances in the filtrate back to the bloodstream.

receptor Involved in maintaining homeostasis; senses changes in the internal environment and sends the information to the control center.

renal tubule A long, narrow tube surrounded by capillaries that reabsorbs many of the filtered substances and secretes other substances; part of the nephron.

rennin Hormone secreted by kidney when blood pressure falls; stimulates the secretion of aldosterone by the adrenal gland. Aldosterone, in turn, stimulates the kidneys to reabsorb more sodium ions and water.

urethra A muscular tube that carries urine out of the body.

urinary system System in which the main function is to filter waste products and excess water from the blood and remove them from the body.

urine The liquid waste product of the body that is excreted by the urinary system.

Points to Consider

- A transplanted kidney may be rejected unless medication is taken to suppress the immune system. Why does the immune system reject transplanted organs?
- How does the immune system recognize transplanted organs as foreign to the body?
- What happens when the immune system "attacks" a transplanted organ?

Image Sources

(1) USDA. *[www.MyPyramid.gov]*. Public Domain.

(2) CK12 Foundation. . CC-BY-SA.

(3) *Patient receiving dialysis treatment.*. Public Domain.

(4) *Good sources of phytochemicals.*. CC-BY-SA.

(5) *Gall stones.*. GFDL.

(6) CK-12 Foundation. *Healthy eating pyramid.*. CC-BY-SA.

(7) *The human kidney.*. Public Domain.

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(13) *The urinary system.*. GFDL.

(14) *Types of human teeth.*. GFDL.

Chapter 24

Immune System and Disease

24.1 Lesson 24.1: Nonspecific Defenses

Lesson Objectives

- Describe mechanical, chemical, and biological barriers that keep most pathogens out of the human body.
- Explain how the inflammatory response and white blood cells help fight pathogens that enter the body.

Introduction

The immune system protects the body from "germs" and other harmful substances. The immune system is like a medieval castle. The outside of a medieval castle was protected by a moat and high stone walls. Inside the castle, soldiers were ready to defend the castle against any invaders that got through the outer defenses. Like a medieval castle, the immune system has a series of defenses. Only pathogens that are able to get through all the defenses can cause harm to the body.

First Line of Defense

The immune system has three lines of defense. The first line of defense includes a variety of barriers against pathogens that keep most pathogens out of the body. Pathogens are disease-causing agents, such as bacteria and viruses. Defenses in the first line are the same regardless of the type of pathogen. This is why they are called nonspecific defenses. Several types of pathogens that are common causes of human disease can be seen in the **Figure** 24.1.

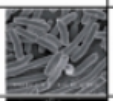
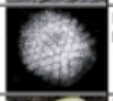
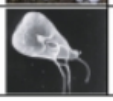
Type of pathogen		Description	Human Disease caused by pathogens of that type
Bacteria Escherichia coli		Single - celled organisms without a nucleus	Strep throat,staph infections, tuberculosis,food poisoning, tetanus,pneumona,syphilis
Viruses Herpes simplex		Non living particles that reproduce by taking over living cells	Common cold,flu,genital herpes, cold sores,measle,AIDS,genital warts,chicken pox,small pox
Fungi Death Cap mushroom		Simple organisms,including mushrooms and yeasts,that grow as single cells or thread like filaments	Ringworm,athlete's foot,tineas, candidiasis,histoplasmosis, mushroom poisoning
Giardia Lamblia		Single celled organism with a nucleus	Malaria,"traveller's diarrhea" giardiasis,typano somiasis ("sleeping sickness")

Figure 24.1: Common Human Pathogens

Mechanical Barriers

Mechanical barriers physically block pathogens from entering the body. The skin is the most important mechanical barrier. In fact, it is the single most important defense of the body against pathogens. It forms a physical barrier between the body and the outside world. The outer layer of the skin is a tough, nearly water-proof coating that is very difficult for pathogens to penetrate.

At body openings, such as the mouth and nose, the body has a different mechanical barrier. Instead of skin, mucous membranes line these and other organs that are exposed to the outside environment. They include the organs of the respiratory, gastrointestinal, and urinary tracts. Mucous membranes secrete mucus, a slimy substance that coats the membranes and traps pathogens. Mucous membranes also have cilia, which are tiny projections that have wavelike motions. The movements of cilia sweep mucus and trapped pathogens toward body openings to be removed from the body.

Pathogens are removed from the respiratory tract when you sneeze or cough. In addition, tears wash pathogens from the eyes, and urine flushes pathogens out of the urinary tract.

Chemical Barriers

Chemical barriers are proteins that destroy pathogens at the body's surface. The skin and mucous membranes secrete proteins that kill many of the pathogens with which they come into contact. For example, enzymes called lysozymes—which are found in sweat, mucus, tears, and saliva—kill pathogens by breaking open their cell walls. Urine and vaginal secretions are too acidic for many pathogens, and semen contains zinc, which most pathogens cannot tolerate. Hydrochloric acid secreted by mucous membranes lining the stomach kills pathogens that enter the stomach in food or water.

Biological Barriers

Biological barriers involve living organisms that compete with pathogens. Human skin is covered by millions of bacteria. Millions more colonize the gastrointestinal, urinary, and genital tracts. Most of these bacteria are helpful or at least not harmful. They are important in defense because they help prevent harmful bacteria from becoming established in or on the body. They do this by competing with harmful bacterial for food and space. Helpful bacteria may also change pH or other factors and make conditions less suitable for harmful bacteria.

Second Line of Defense

If you have a cut on your hand, the break in the skin provides a way for pathogens to enter your body. Assume bacteria enter through the cut and infect the wound. These bacteria would then encounter the second line of defense.

Inflammatory Response

The cut on your hand is likely to become red, warm, swollen, and painful. These are all signs that an inflammatory response has occurred. An inflammatory response is a complex biological reaction to tissue damage. It is one of the first responses of the immune system to infection or injury. Inflammation is triggered by chemicals called cytokines and histamines, which are released when tissues are damaged.

- Cytokines are chemical signals used to communicate between cells.
- Histamines are chemicals that cause inflammation and allergies.

The cytokines and histamines released when tissue is damaged cause many changes in the damaged tissue. The changes help remove the cause of the damage and start the healing process. For example, the chemicals cause local blood vessels to dilate, which increases blood flow to the area. They also cause other changes in blood vessels that allow blood components to leak into the damaged tissue.

White Blood Cells

Another role of cytokines is to attract white blood cells, or leukocytes, to the site of inflammation. Leukocytes are immune system cells that are specialized to fight infections. They are the primary cells of the immune system and found throughout the body. The general function of leukocytes is to identify and eliminate pathogens, debris, and abnormal body cells. **Figure** 24.2 shows several different types of leukocytes. Each type plays a different role in the removal of pathogens and other unwanted substances from the body.

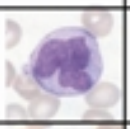
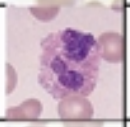
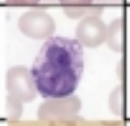
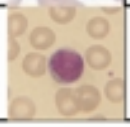
Type of Leucocyte	Approximate percent of all Leukocytes	Roles in Defense and other Actions
Monocyte, Macrophage 	<6%	Phagocytosis; releasing cytokines
Neutrophil 	65%	Phagocytosis; fighting fungus infections
Eosinophil 	4%	Fighting protozoan infections
Basophil 	<1%	Releaasing histamines
Lymphocyte 	25%	Making antibodies; destroying cells infected by pathogens

Figure 24.2: Types of Leukocytes

Some leukocytes are nonspecific and respond in the same way to most pathogens. Nonspecific leukocytes include monocytes, macrophages, neutrophils, eosinophils, and basophils. These leukocytes are part of the second line of defense. A magnified image of an actual macrophage is shown in **Figure** 24.3.

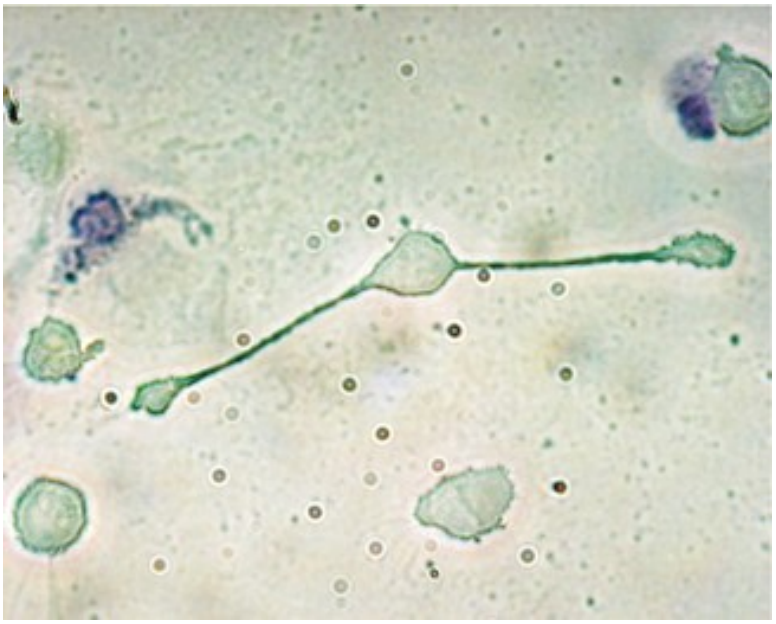


Figure 24.3: Magnified image of a macrophage.

Monocytes, macrophages, and neutrophils destroy pathogens in the blood and tissues by phagocytosis. Phagocytosis is the process of engulfing and breaking down pathogens and other unwanted substances. Phagocytosis of a pathogen by a macrophage is illustrated in **Figure** 24.4. Once a pathogen has been engulfed, it is broken down within the macrophage. Macrophages are found in tissues, and monocytes and neutrophils are found in the blood.

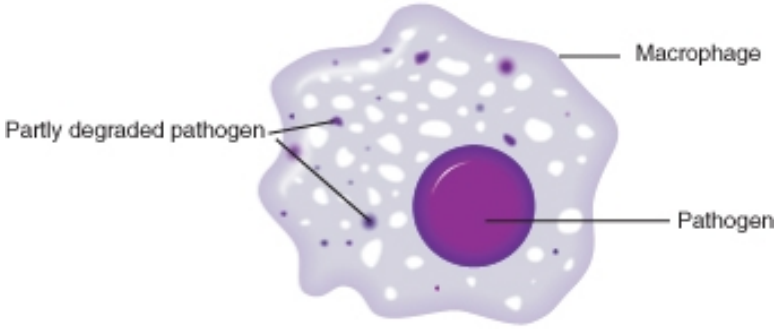


Figure 24.4: Phagocytosis by a macrophage.

Both monocytes and neutrophils migrate through the bloodstream to sites of inflammation.

Neutrophils are the most common leukocytes and usually the first leukocytes to arrive at the scene of infection. Neutrophils and dead pathogens are the main components of pus.

In addition to phagocytosis, both monocytes and phagocytes produce chemicals such as cytokines that cause inflammation and fever. A fever is a higher-than-normal body temperature that may help fight infection. Monocytes or macrophages may also trigger the third line of defense, which you will read about in Lesson 24.2: Immune Response.

Eosinophils and basophils are responsible for allergies, which are discussed in Lesson 24.3: Immune System Diseases. Eosinophils also help fight infections by combating parasites such as protozoa. Basophils release cytokines, histamines, and other chemicals that contribute to inflammation as well as allergies.

Lymphocytes are different from these nonspecific leukocytes. Lymphocytes launch an attack that is tailored to a particular pathogen. For example, some lymphocytes attack only herpes viruses, others only flu viruses. This is called a specific defense. This type of defense is the topic of the next lesson.

Lesson Summary

- Mechanical, chemical, and biological barriers are the body's first line of defense against pathogens.
- The inflammatory response and phagocytosis by white blood cells are major components of the body's second line of defense.

Review Questions

1. Identify two defenses in the body's first line of defense.
2. Describe the process of phagocytosis.
3. How does the inflammatory response help fight infections?
4. Describe the roles of leukocytes in the body's second line of defense.

Further Reading / Supplemental Links

- Farrell, Jeanette, Invisible Enemies: Stories of Infectious Disease. Farrar, Straus and Giroux, 2005.
- http://en.wikibooks.org/wiki/Human_Physiology/The_Immune_System
- http://www.clevelandclinic.org/health/health-info/docs/0200/0217.asp?index=4857
- http://library.thinkquest.org/C0115080/?c=wbc
- http://www.sciencedaily.com/releases/2007/07/070711135623.htm
- http://en.wikipedia.org

Vocabulary

biological barriers Living organisms that compete with pathogens; help prevent harmful bacteria from becoming established in or on the body.

chemical barriers Proteins that destroy pathogens at the body's surface.

cytokines Chemical signals used to communicate between cells.

fever A higher-than-normal body temperature that may help fight infection.

histamines Chemicals that cause inflammation and allergies.

inflammatory response A complex biological reaction to tissue damage; one of the first responses of the immune system to infection or injury; triggered by chemicals called cytokines and histamines.

lysozymes Enzymes that kill pathogens by breaking open their cell walls; found in sweat, mucus, tears, and saliva.

mechanical barriers Physically blocks pathogens from entering the body; the skin is the most important mechanical barrier.

mucus A slimy substance secreted by mucus membranes; coats the membranes and traps pathogens.

nonspecific defenses Defenses that are the same regardless of the type of pathogen; found in the first and second line of defense.

pathogens Disease-causing agents, such as bacteria and viruses.

phagocytosis The process of engulfing and breaking down pathogens and other unwanted substances.

white blood cells Leukocytes; immune system cells that are specialized to fight infections; they identify and eliminate pathogens, debris, and abnormal body cells; leukocytes includes monocytes, macrophages, neutrophils, eosinophils, and basophils.

Points to Consider

The body's first and second lines of defense are the same regardless of the particular pathogen involved. The body's third line of defense is different. It defends the body against specific pathogens.

- Think about how the immune system could identify a particular pathogen.
- Can you develop possible mechanisms for how these pathogens could be destroyed?
- What roles do you think various cell types (such as lymphocytes) play in the specific defenses of the immune system?

24.2 Lesson 24.2: Immune Response

Lesson Objectives

- Describe the lymphatic system and state its general functions in the immune response.
- Explain the role of antigens in the immune response.
- List the steps that occur in a humoral immune response.
- Identify roles of different types of T cells in a cell-mediated immune response.
- Define immunity and distinguish between active and passive immunity.

Introduction

If pathogens manage to get through the body's first two lines of defense, a third line of defense takes over. This third line of defense is often referred to as the immune response. This defense is specific to a particular pathogen, and it allows the immune system to "remember" the pathogen after the infection is over. If the pathogen tries to invade the body again, the immune system can launch a much faster, stronger attack. This lets the immune system destroy the pathogen before it can cause harm. The immune response mainly involves the lymphatic system.

Lymphatic System

The lymphatic system is a major component of the immune system. Because of its important role in the immune system, the terms "immune system" and "lymphatic system" are sometimes used interchangeably. However, as you read in Lesson 24.1, nonspecific defenses of the body include organs such as the skin, which is not part of the lymphatic system. In addition, the lymphatic system has another function not directly related to defense.

Functions of the Lymphatic System

The lymphatic system has three basic functions. The first function is related to digestion. The other functions are involved in the immune response.

1. The lymphatic system absorbs fatty acids after the digestion of lipids in the small intestine. It then transports the fatty acids to the bloodstream, where they circulate throughout the body.
2. The lymphatic system removes excess fluid from body tissues and returns the fluid to the blood. The fluid is filtered as it passes through the lymphatic system, and any pathogens it contains are destroyed before the fluid enters the bloodstream.
3. The lymphatic system produces lymphocytes. Lymphocytes are the type of white blood cells, or leukocytes, primarily involved in the immune response. They recognize and help destroy specific foreign invaders in body fluids and cells.

Parts of the Lymphatic System

The lymphatic system, which is shown in **Figure** 24.5, consists of lymphatic organs, lymphatic vessels, lymph, and lymph nodes. Organs of the lymphatic system include the red bone marrow, thymus, spleen, and tonsils.

- Red bone marrow is found inside many bones, including the hip, breast, and skull bones. It produces leukocytes.
- The thymus is a gland located in the upper chest behind the breast bone. It stores and matures lymphocytes.
- The spleen is a gland in the upper abdomen. It filters blood and destroys worn-out red blood cells. Lymphocytes in the spleen destroy any pathogens filtered out of the blood.
- Tonsils are glands on either side of the pharynx in the throat. They trap pathogens, which are then destroyed by lymphocytes in the tonsils.

Lymphatic vessels make up a body-wide circulatory system, similar to the arteries and veins of the cardiovascular system. However, lymphatic vessels circulate lymph instead of blood. Lymph is fluid that leaks out of tiny blood vessels, called capillaries, into spaces between cells in tissues. At sites of inflammation, there is usually more lymph around cells, and it is likely to contain many pathogens.

Unlike the cardiovascular system, the lymphatic system does not have a pump to force lymph through its vessels. Lymph circulates due to peristalsis of lymphatic vessels and rhythmic contractions of the skeletal muscles that surround the vessels. Valves in the lymphatic vessels prevent lymph from flowing backwards through the system.

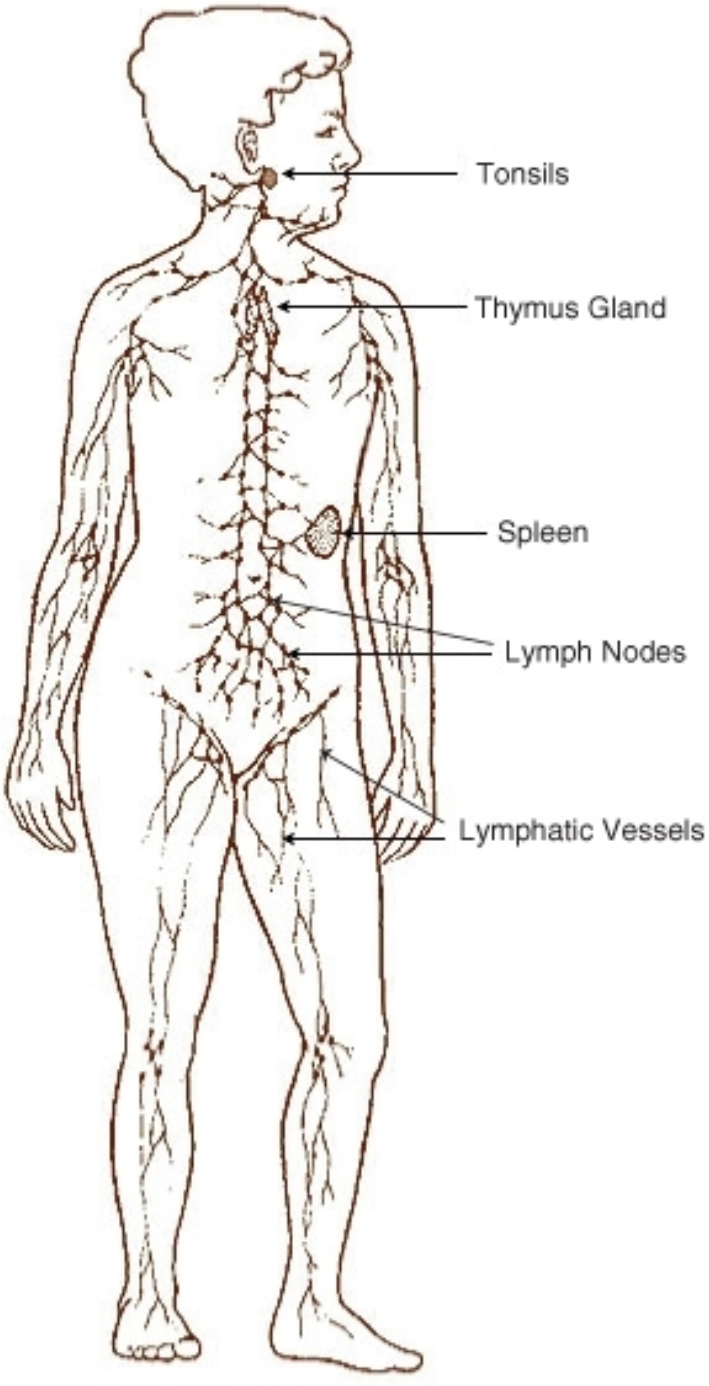


Figure 24.5: Human lymphatic system.

As lymph accumulates between cells, it diffuses into tiny lymphatic vessels. The lymph then moves through the lymphatic system, from smaller to larger vessels, until it reaches the main lymphatic ducts in the chest. Here, the lymph drains into the bloodstream.

Before lymph reaches the bloodstream, pathogens are filtered out of it at lymph nodes. Lymph nodes are small, oval structures located along the lymphatic vessels that act like filters. Any pathogens filtered out of the lymph at lymph nodes are destroyed by lymphocytes in the nodes.

Lymphocytes

Lymphocytes are the key cells involved in the immune response. There are an estimated two trillion lymphocytes in the human body, and they make up about 25 percent of all leukocytes. Usually, fewer than half the body's lymphocytes are found in the blood. The rest are found in the lymphatic system, where they are most likely to encounter pathogens.

The immune response depends on two types of lymphocytes: B lymphocytes, or B cells, and T lymphocytes, or T cells. Both types of lymphocytes are produced in the red bone marrow. The two types are named for the sites where they mature. B cells mature in the red bone marrow, and T cells mature in the thymus. Both B and T cells can recognize and respond to specific pathogens. B or T cells that respond to the body's own molecules as though they were foreign, or "nonself," receive a signal that causes them to die. Only those B and T cells that have shown they are unlikely to react to "self" molecules are released into the circulation.

Antigen Recognition

B and T cells do not actually recognize and respond to pathogens but to the antigens they carry. Antigens are protein molecules that the immune system recognizes as nonself. Any protein that can trigger an immune response because it is foreign to the body is called an antigen. Antigens include proteins on pathogens, cancer cells, and the cells of transplanted organs.

Antigen Receptors

Both B and T cells can "recognize" specific antigens because they have receptor molecules on their surface that bind to particular antigen molecules or pieces of antigen molecules. As shown in **Figure** 24.6, the fit between a receptor molecule and a specific antigen is like a lock and key. Receptors on each B or T cell recognize and bind to just one type of antigen. The human body makes lymphocytes with receptor sites for a huge number of possible antigens that may be encountered throughout a person's life.

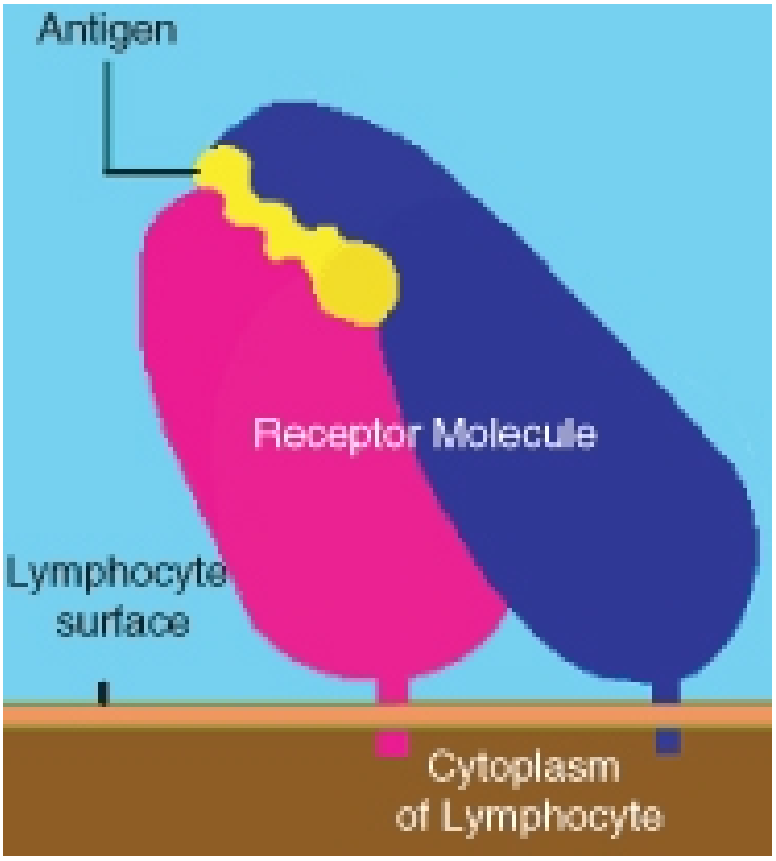


Figure 24.6: A receptor molecule on the surface of a lymphocyte binds to a particular antigen like a lock and key.

Activation of Lymphocytes

Before lymphocytes can function, they must be activated. Activation occurs the first time the cells encounter their specific antigens after leaving the red bone marrow or thymus. Until these circulating B and T cells have been activated, they are called "naïve" cells.

Humoral Immune Response

B cells are responsible for the humoral immune response. The humoral immune response takes place in blood and lymph and involves the production of antibodies. Antibodies are large, Y-shaped proteins called immunoglobulins (Ig) that recognize and bind to antigens. In humans (and other mammals) there are five types of immunoglobulins: IgA, IgD, IgE, IgG, and IgM. Antibodies are produced by activated B cells.

B Cell Activation

Naïve B cells are activated by an antigen in the sequence of events shown in **Figure** 24.7. A B cell encounters its matching antigen and engulfs it. The B cell then displays fragments of the antigen on its surface. This attracts a helper T cell (which you will read about below). The helper T cell binds to the B cell at the antigen site and releases cytokines. As you read in Lesson 24.1, cytokines are chemical signals used to communicate between cells. Cytokines from the helper T cell stimulate the B cell to develop into plasma cells or memory cells.

Plasma Cells and Antibody Production

Plasma cells are activated B cells that secrete antibodies. They are specialized to act like antibody factories. Antibodies produced by plasma cells circulate in the blood and lymph. Each antibody recognizes and binds to a specific antigen, depending on the plasma cell that produced it and other factors. The binding of an antibody to its matching antigen forms an antigen-antibody complex, as shown in **Figure** 24.8. An antigen-antibody complex flags a pathogen or foreign cell for destruction by phagocytosis. The liver removes antigen-antibody complexes from the blood and the spleen removes them from the lymph.

Memory Cells

Whereas most plasma cells live just a few days, memory cells live much longer. They may even survive for the lifetime of the individual. Memory cells are activated B (or T) cells that retain a "memory" of a specific pathogen long after an infection is over. They help launch a rapid response against the pathogen if it invades the body in the future. Memory B cells

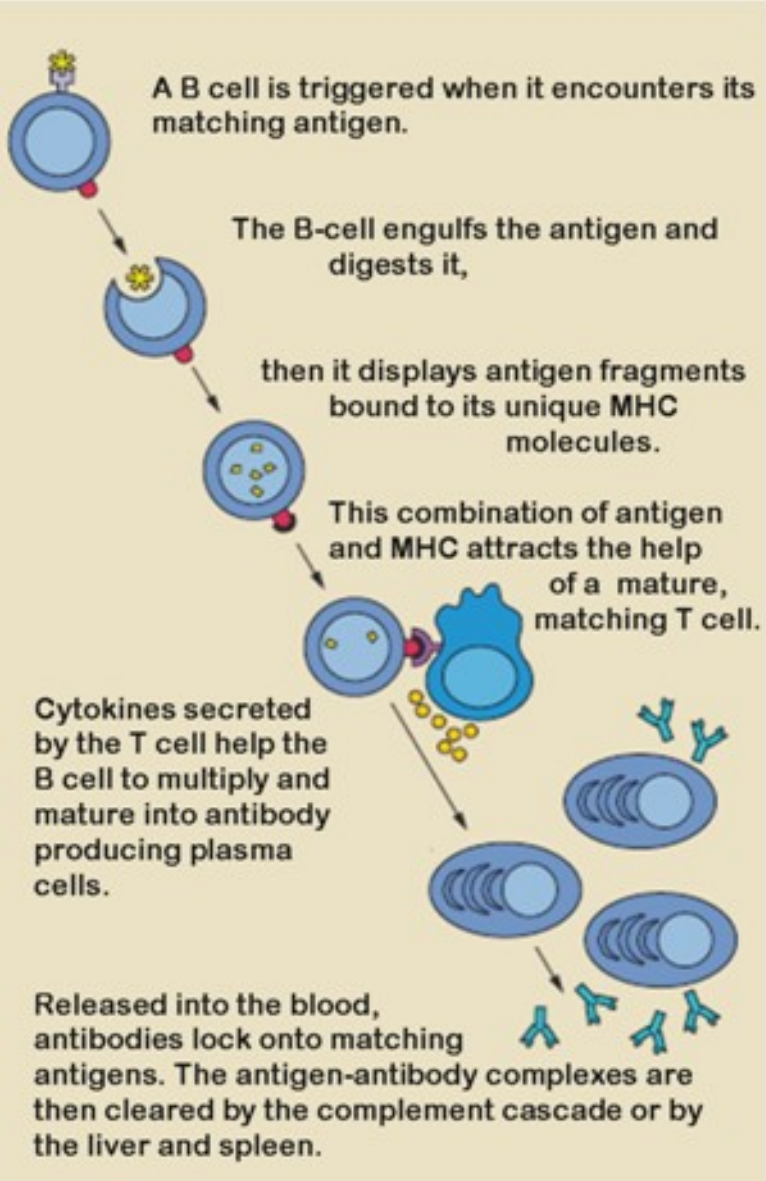


Figure 24.7: After engulfing an antigen, a naïve B cell presents the antigen to a mature T cell. The T cell, in turn, releases cytokines that activate the B cell. Once activated, the B cell can produce antibodies to that particular pathogen.

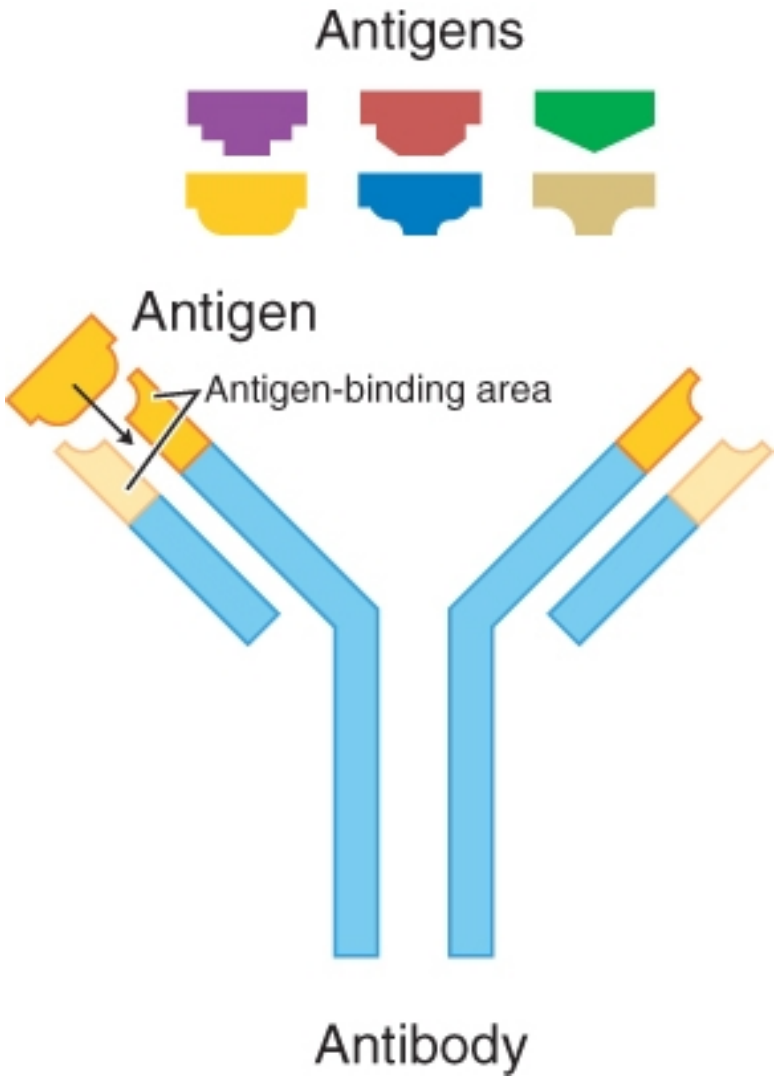


Figure 24.8: An antibody molecule has an area that "fits" one particular antigen. This area is where the antigen binds to the antibody, creating an antigen-antibody complex.

remain in the lymph, ready to produce specific antibodies against the same pathogen if it shows up in body fluids again.

Cell-Mediated Immune Response

There are several different types of T cells, including helper, cytotoxic, memory, and regulatory T cells. T cells are responsible for cell-mediated immunity. Cell-mediated immunity involves the destruction of body cells that are infected with pathogens or have become damaged or cancerous.

T Cell Activation

The different types of naïve T cells are activated in the same general way. The mechanism is shown in **Figure** 24.9. It involves B cells or leukocytes such as macrophages. These other cells engulf pathogens in phagocytosis and display parts of the pathogens' antigens on their surface. The cells are then called antigen-presenting cells. When a naïve T cell encounters one of these cells with an antigen matching its own, it begins the activation process. After T cells are activated, the various types of T cells play different roles in the immune response.

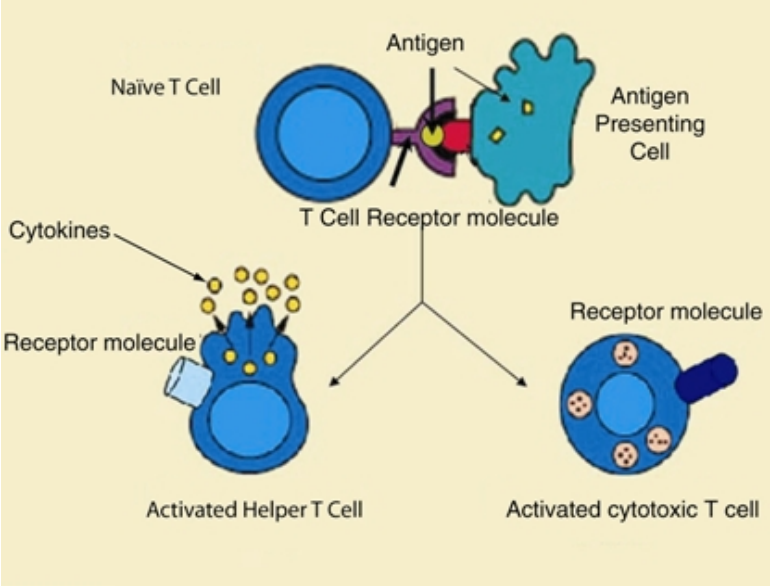


Figure 24.9: A naïve T cell is activated when it encounters a B cell or macrophage that has engulfed a pathogen and presents the pathogen's antigen on its surface.

Helper T Cells

Activated helper T cells do not kill pathogens or destroy infected cells, but they are still necessary for the immune response. In fact, they are considered to be the "managers" of the immune response. After activation, helper T cells divide rapidly and secrete cytokines. These chemical signals control the activity of other lymphocytes. As mentioned above, cytokines from helper T cells activate B cells. They also activate other T cells.

Most activated helper T cells die out once a pathogen has been cleared from the body. However, some helper T cells remain in the lymph as memory cells. These memory cells are ready to produce large numbers of antigen-specific helper T cells if they are exposed to the same antigen again in the future.

Cytotoxic T Cells

Helper cells are needed to activate cytotoxic T cells. Activated cytotoxic T cells destroy tumor cells, damaged cells, and cells infected with viruses. They are also involved in the rejection of transplanted organs. Once activated, a cytotoxic T cell divides rapidly and produces an "army" of cells identical to itself. These cells travel throughout the body "searching" for more cells carrying their specific antigen. Whenever they encounter the cells, they destroy them. Illustrated in **Figure** 24.10 is how a cytotoxic T cell destroys a body cell infected with viruses. The cytotoxic T cell releases toxins that form pores, or holes, in the infected cell's membrane. This causes the cell to burst, destroying both the cell and the viruses inside it.

After cytotoxic T cells bring a viral infection under control, most of the cytotoxic T cells die off. However, some of them remain as memory cells. If the same pathogen tries to infect the body again, the memory cells mount an effective immune response by producing a new army of antigen-specific cytotoxic T cells.

Regulatory T Cells

Regulatory T cells shut down cell-mediated immunity toward the end of an immune response. They also try to suppress any T cells that react against self antigens as though they were foreign. This occurs in automimmune diseases, which you will read about in Lesson 24.3.

Immunity

Memory B and T cells help protect you from re-infection by pathogens that have infected you in the past. Being able to resist a pathogen in this way is called immunity. Immunity can be active or passive.

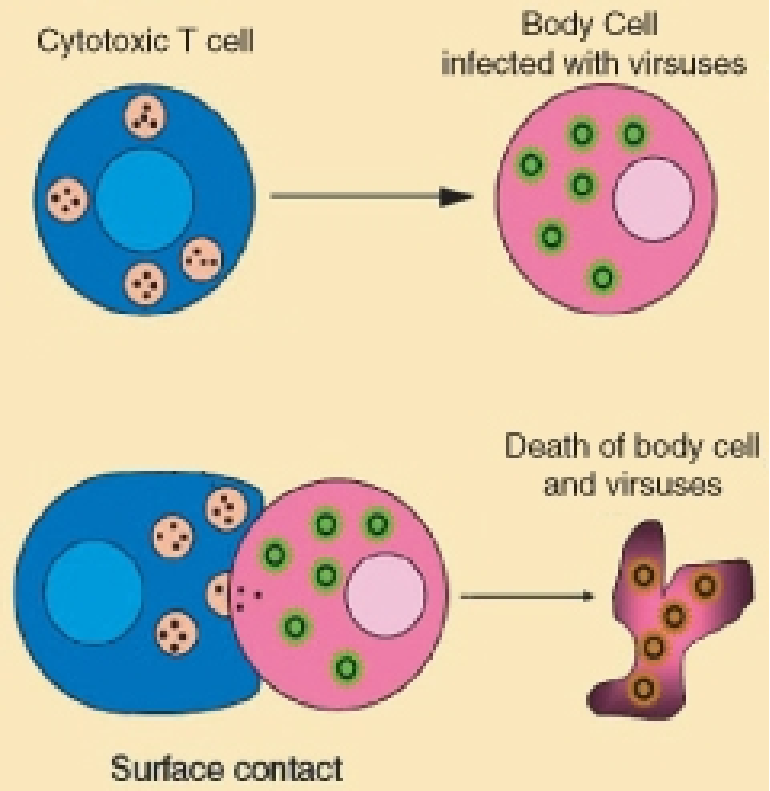


Figure 24.10: A cytotoxic T cell releases toxins that destroy an infected body cell and the viruses it contains.

Active Immunity

Active immunity is immunity that results from a pathogen stimulating an immune response and leaving you with memory cells for the specific pathogen. This happens when a pathogen infects your body and makes you sick. As long as the memory cells survive, the pathogen will be unlikely to re-infect you and make you sick again. In the case of some pathogens, memory cells and active immunity last for the life of the individual.

Active immunity can also occur through immunization. Immunization is deliberate exposure of a person to a pathogen in order to provoke an immune response. The purpose of immunization is to prevent actual infections by the pathogen. The pathogen is typically injected. However, only part of a pathogen, a weakened form of the pathogen, or a dead pathogen is used. This provokes an immune response without making you sick. Diseases you have likely been immunized against include measles, mumps, rubella, whooping cough, and chicken pox.

Passive Immunity

Passive immunity is humoral immunity that results when antibodies to a specific pathogen are transferred to an individual who has never been exposed to the pathogen before. Passive immunity lasts only as long as the antibodies survive in body fluids, generally between a few days and several months.

Passive immunity is acquired by a fetus when it receives antibodies from the mother's blood. It is acquired by an infant when it receives antibodies from the mother's milk. Older children and adults can acquire passive immunity through injection of antibodies into the blood. Injection of antibodies is sometimes used as treatment for a disease, such as measles, when people have not been immunized against the disease.

Lesson Summary

- The lymphatic system is a major component of the immune system. It filters pathogens from lymph and produces lymphocytes, which are the key cells in an immune response.
- Antigens are proteins that the immune system recognizes as foreign to the body. They trigger the activation of lymphocytes.
- Activated B cells produce antibodies against a pathogen's antigens. Long-lasting memory B cells remain in the body to provide immunity to the specific pathogen.
- Activated T cells destroy tumor cells and cells infected with viruses. Memory T cells remain after an infection to provide antigen-specific immunity.
- Immunity is the ability to resist infection by a pathogen. It can occur by having an immune response to a pathogen or receiving antibodies to a pathogen.

Review Questions

1. List three parts of the lymphatic system and their functions.
2. What are antigens and how do lymphocytes "recognize" them?
3. How do plasma cells form and help fight pathogens?
4. Describe how cytotoxic T cells destroy cells infected with viruses.
5. What type of immune response would occur if bacteria invaded your lymph? Explain your answer.
6. Explain how immunization prevents a disease such as measles.
7. If a disease destroyed a person's helper T cells, how might this affect the immune response?
8. Compare and contrast humoral and cell-mediated immune responses.

Further Reading / Supplemental Links

- Panno, Joseph, Ph.D., Immune System. Facts on File, 2008.
- http://en.wikibooks.org/wiki/Human_Physiology/The_Immune_System
- http://www.acm.uiuc.edu/sigbio/project/lymphatic/index.html
- http://www.cancer.gov/cancertopics/understandingcancer/immunesystem
- http://www.howstuffworks.com/immune-system.htm
- http://www.kidshealth.org/parent/general/body_basics/immune.html
- http://www.kidshealth.org/parent/general/body_basics/spleen_lymphatic.html
- http://www.lymphomation.org/lymphatic.htm
- http://www.niaid.nih.gov/final/immun/immun.htm
- http://www.niaid.nih.gov/publications/immune/the_immune_system.pdf
- http://www.sciencedaily.com/releases/2007/08/070802181939.htm
- http://www.thebody.com/content/art1788.html
- http://en.wikipedia.org

Vocabulary

active immunity Immunity that results from a pathogen stimulating an immune response and leaving you with memory cells for the specific pathogen.

antibody Large, Y-shaped proteins called immunoglobulins (Ig) that recognize and bind to antigens; produced by activated B cells. In humans (and other mammals) there are five types of immunoglobulins: IgA, IgD, IgE, IgG, and IgM.

antigen Any protein that can trigger an immune response because it is foreign to the body; includes proteins on pathogens, cancer cells, and the cells of transplanted organs.

antigen receptor A receptor molecule on the surface of a lymphocyte that binds to a particular antigen like a lock and key.

B lymphocytes (B cells) Lymphocytes that are produced in the red bone marrow and mature in the red bone marrow; can recognize and respond to specific pathogens.

cell-mediated immunity Involves the destruction of body cells that are infected with pathogens or have become damaged or cancerous.

cytotoxic T cells Cells that destroy tumor cells, damaged cells, and cells infected with viruses.

helper T cells Considered to be the "managers" of the immune response. After activation, helper T cells divide rapidly and secrete cytokines. These chemical signals control the activity of other lymphocytes.

immunity Protection from re-infection by pathogens that have infected you in the past.

immune response The third line of defense; specific to a particular pathogen.

immunization The deliberate exposure of a person to a pathogen in order to provoke an immune response.

lymph Fluid that leaks out of tiny blood vessels, called capillaries, into spaces between cells in tissues.

lymph nodes Small, oval structures located along the lymphatic vessels that act like filters; pathogens filtered out of the lymph at lymph nodes are destroyed by lymphocytes in the nodes.

lymphatic system System that makes lymphocytes; consists of lymphatic organs, lymphatic vessels, lymph, and lymph nodes. Organs of the lymphatic system include the red bone marrow, thymus, spleen, and tonsils.

lymphatic vessels Form a body-wide circulatory system, similar to the arteries and veins of the cardiovascular system; circulate lymph instead of blood.

lymphocytes Type of white blood cells, or leukocytes, primarily involved in the immune response; recognize and help destroy specific foreign invaders in body fluids and cells.

memory cells Memory cells are activated B (or T) cells that retain a "memory" of a specific pathogen long after an infection is over; help launch a rapid response against the pathogen if it invades the body in the future.

passive immunity A humoral immunity that results when antibodies to a specific pathogen are transferred to an individual who has never been exposed to the pathogen before.

phagocytosis The process of engulfing and breaking down pathogens and other unwanted substances.

plasma cells Activated B cells that secrete antibodies.

red bone marrow Found inside many bones, including the hip, breast, and skull bones; produces leukocytes.

regulatory T cells T cells that shut down cell-mediated immunity toward the end of an immune response; also try to suppress any T cells that react against self antigens as though they were foreign.

spleen A gland in the upper abdomen; filters blood and destroys worn-out red blood cells. Lymphocytes in the spleen destroy any pathogens filtered out of the blood.

T lymphocytes (T cells) Lymphocytes that are produced in the red bone marrow and mature in the thymus; can recognize and respond to specific pathogens; includes helper, cytotoxic, memory, and regulatory T cells.

thymus A gland located in the upper chest behind the breast bone; stores and matures lymphocytes.

tonsils Glands on either side of the pharynx in the throat; traps pathogens, which are then destroyed by lymphocytes in the tonsils.

Points to Consider

- Sometimes the immune system makes mistakes and things go wrong. What if the immune system responded to a harmless allergen as though it were a deadly pathogen?
- What if the immune system responded to normal body cells as though they were foreign invaders?
- What if pathogens attacked and destroyed cells of the immune system itself? Would it still be able to function?

24.3 Lesson 24.3: Immune System Diseases

Lesson Objectives

- Explain how allergies occur and list common allergens.
- Describe how autoimmune diseases affect the body.
- Define immunodeficiency and identify ways it can be acquired.
- Explain how HIV is transmitted and how it causes AIDS.

Introduction

The immune system usually protects you from pathogens and keeps you well. However, like any other body system, the immune system can malfunction or become diseased. Sometimes the immune system responds to harmless foreign substances as though they were pathogens. Sometimes it mistakes self for nonself and launches an attack against the body's own cells. Certain diseases can also attack and damage the immune system so it loses the ability to defend the body.

Allergies

An allergy is a disease in which the immune system makes an inflammatory response to a harmless antigen. Any antigen that causes an allergic reaction is called an allergen. You can be exposed to allergens by inhaling or ingesting them or by having direct skin contact with them.

Allergies can vary greatly from person to person. Some people are allergic to many allergens, others to few or none. A tendency to develop allergies can be inherited, so if your mom or dad has allergies, you are more likely to have them as well. Allergy symptoms may be mild or severe. They may develop immediately after exposure to an allergen or not until several days after exposure.

Severity of Allergies

Allergy symptoms are caused by the release of histamines, the chemicals that also stimulate inflammation. The symptoms range from scarcely noticeable to potentially fatal. Typical symptoms of mild allergies include itchy eyes, sneezing, and skin rashes. These symptoms may be uncomfortable, but they are not life threatening. Mild allergy symptoms are often treated with antihistamines. Antihistamines are drugs that reduce or eliminate the effects of histamines.

Immunotherapy, commonly called "allergy shots," is sometimes recommended for more se-

vere allergies. A person with an allergy is injected with larger and larger amounts of the offending allergen over a period of months or years. This gradually desensitizes the person's immune system to the allergen. Rather than just treating the symptoms of the allergy, immunotherapy reduces the severity of the allergy or eliminates the allergy altogether.

The most severe allergic reaction is anaphylaxis. Anaphylaxis is an allergic response in which there is a sudden, massive release of histamines throughout the body. This causes collapse of the circulatory system and severe constriction of the breathing passages. Without emergency treatment, anaphylaxis is likely to be fatal. Treatment is usually injection of epinephrine. Epinephrine is the "fight-or-flight" hormone that your adrenal glands normally produce when you are in danger. The hormone suppresses non-emergency body processes, including the immune response.

Immediate Hypersensitivity Reaction

When exposure to an antigen causes immediate allergy symptoms, the response is called an immediate hypersensitivity reaction. This is a humoral immune response. Examples of allergens that cause this type of reaction include pollens, bee stings, and peanuts. Anaphylaxis may occur if the allergy is severe.

Allergic rhinitis is a common immediate hypersensitivity reaction. It affects mainly mucous membranes lining the nose. Typical symptoms include runny nose and nasal congestion. Pollens are the most common cause of allergic rhinitis. Tiny pollens of wind-pollinated plants like ragweed (**Figure** 24.11) are the usual culprits. Other causes of allergic rhinitis include mold, animal dander, and dust. Allergic rhinitis may occur seasonally or year-round, depending on its cause.

Allergic rhinitis is often called hay fever, although pollen—not hay—is the most likely cause. It is called hay fever because it is most common during the time of year when hay is cut. This is also the time of year when plant pollens are most concentrated in outdoor air.

Delayed Hypersensitivity Reaction

When an antigen causes allergy symptoms hours or days after exposure, the response is called a delayed hypersensitivity reaction. This is a cell-mediated immune response. Examples of allergens that cause delayed hypersensitivity reactions include poison ivy, poison oak, and poison sumac. If you have skin contact with these plants and are allergic to them, a rash, like the one in **Figure** 24.12, may develop.

Figure 24.11: Ragweed, a common cause of allergic rhinitis.

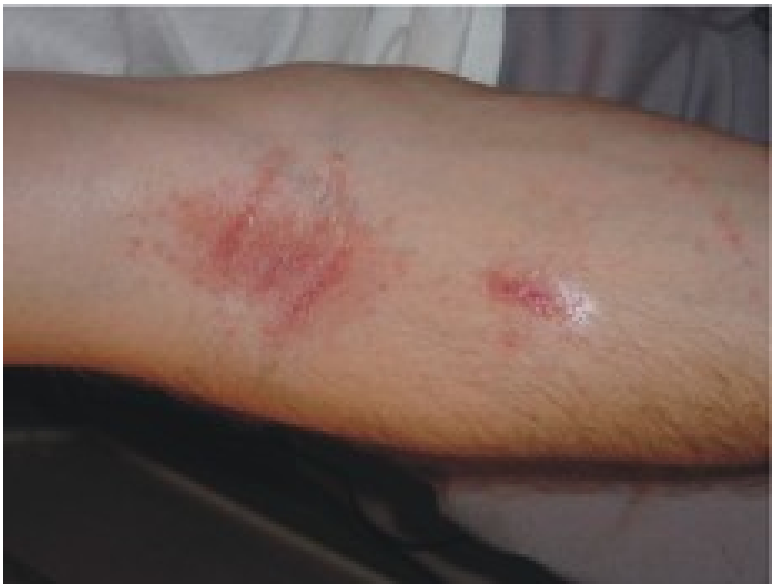


Figure 24.12: Allergic rash caused by contact with poison ivy.

Autoimmune Diseases

Autoimmune diseases occur when the immune system fails to recognize the body's own molecules as self and attacks the body's cells as though they were foreign invaders. Relatively common autoimmune diseases include rheumatoid arthritis, type 1 diabetes mellitus, multiple sclerosis, and systemic lupus erythematosus (**Table** 24.1). These four diseases are described in the table below. They are currently incurable, but treatment can help relieve the symptoms and prevent some of the long-term damage.

Table 24.1: **Common Autoimmune Diseases**

Autoimmune Disease	Object of Immune Attack	Results of Immune Attack	Treatment(s)
Rheumatoid arthritis	Tissues inside joints	Inflammation of joints, causing joint pain and damage and possible loss of mobility	Anti-inflammatory drugs; drugs that suppress the immune system
Type 1 diabetes	Insulin-producing cells of the pancreas	Loss of ability to produce insulin, causing too much sugar in the blood and tissue and organ damage	Insulin injections

Table 24.1: (continued)

Autoimmune Disease	Object of Immune Attack	Results of Immune Attack	Treatment(s)
Multiple sclerosis	Myelin in the brain and spinal cord	Loss of nerve function, causing muscle weakness, fatigue, visual problems, pain, and other symptoms	Corticosteroid drugs; hormones that control the immune system
Systemic lupus erythematosus	Joints, heart, lungs, or other organs	Inflammation of joints or organs, causing serious joint or organ damage and pain	Corticosteroid drugs; drugs that suppress the immune system

The causes of autoimmune diseases are not known for certain. One way autoimmunity may develop is through "molecular mimicry." This occurs when a person is infected with pathogens bearing antigens similar to the person's own molecules. When the immune system mounts an attack against the pathogens, it also attacks body cells with the similar molecules. Some people inherit genes that increase their risk for an autoimmune disease. Female sex hormones may also increase the risk. This may explain why autoimmune diseases are more common in females than males and why they usually begin after puberty.

Immunodeficiency Diseases

Immunodeficiency occurs when one or more components of the immune system are not working normally. As a result, the ability of the immune system to respond to pathogens and other threats is decreased. A person with immunodeficiency may suffer from frequent, life-threatening infections. In other words, an individual with a compromised immune system (for example, a person with AIDS) may be unable to fight off and survive infections by microorganisms that are usually benign. Immunodeficiency can be present at birth or acquired after birth.

Congenital Immunodeficiency

Congenital immunodeficiency is present at birth and usually caused by a genetic disorder. Such disorders are relatively rare. For example, thymic aplasia—a genetic disorder characterized by an absent or abnormal thymus—occurs in about 1 out of 4,000 births. People with thymic aplasia are unable to produce normal T cells. They have frequent infections and increased risk of autoimmune diseases.

Acquired Immunodeficiency

Acquired immunodeficiency occurs when immune function declines in a person who was born with a normal immune system. There are many possible causes for declining immune function. Age is one cause. The immune system naturally becomes less effective as we get older, starting in middle adulthood. This helps explain why older people are more susceptible to disease. Other possible causes of declining immune function include obesity, alcoholism, and illegal drug abuse. In developing countries, malnutrition is a common cause.

Many medications can interfere with normal immune function and cause immunodeficiency. Immune suppressive drugs are deliberately given to people with autoimmune diseases and transplanted organs. Many other drugs have immune suppression as a side effect. Chemotherapy drugs for cancer are especially likely to suppress the immune system.

Several kinds of cancer attack cells of the immune system and cause immunodeficiency. For example, in chronic lymphatic leukemia, abnormal B cells that can't fight infection grow out of control and crowd out healthy B cells. Certain pathogens can also attack cells of the immune system. In fact, the virus known as HIV is the most common cause of immunodeficiency in the world today.

HIV and AIDS

HIV, or human immunodeficiency virus, is the virus that causes AIDS. AIDS stands for acquired immune deficiency syndrome. It is a late stage in the progression of an HIV infection.

HIV Transmission

HIV is transmitted, or spread, through direct contact of mucous membranes or the bloodstream with a body fluid containing HIV. Body fluids that can contain HIV include blood, semen, vaginal fluid, preseminal fluid, and breast milk. Transmission of the virus can occur through sexual contact or use of contaminated hypodermic needles. HIV can also be transmitted through a mother's blood to her baby during late pregnancy or birth or through breast milk after birth. In the past, HIV was transmitted through blood transfusions. Because donated blood is now screened for HIV, the virus is no longer transmitted this way.

HIV and the Immune System

HIV destroys helper T cells. Recall that helper T cells are needed for normal humoral and cell-mediated immunity. When HIV enters a person's bloodstream, proteins on the coat of the virus allow it to fuse with the host's helper T cells. The virus injects its own DNA into the host's helper T cells and uses the T cells' "machinery" to make copies of itself. The

copies of the virus bud off from the host's cells, destroying the cells in the process. Copies of the virus go on to infect other helper T cells throughout the body.

During the first several weeks after HIV infection, the immune system tries to fight off the virus. As shown in **Figure** 24.13, the initial immune response temporarily reduces the number of virus copies in the blood. However, the immune system is unable to destroy the virus, and it continues to multiply in the lymphatic system. How is HIV able to evade the immune system? There are at least two ways:

- The virus undergoes frequent mutations that keep changing the antigens on its coat. This prevents antigen-specific lymphocytes from developing that could destroy the virus.
- The virus uses the host's cell membranes to form is own coat. This covers up viral antigens so they cannot be detected by the host's immune system.

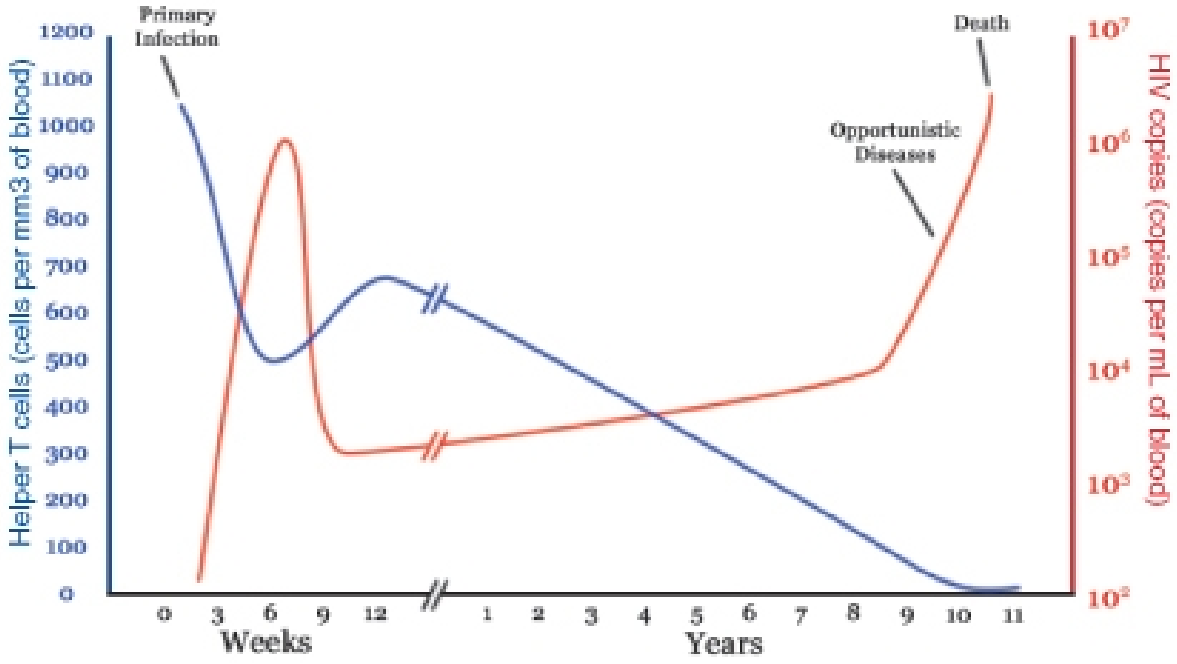


Figure 24.13: Average numbers of helper T cells and HIV copies in untreated HIV infections.

Over the next several years, helper T cells continuously decline in the blood, while copies of the virus keep increasing. As the number of helper T cells declines, so does the ability of the immune system to make an immune response. The HIV-infected person starts showing symptoms of a failing immune system, such as frequent infections.

Treatment with antiviral medications can slow down the increase in virus copies, although they do not eliminate the virus altogether. The medications usually lengthen the time

between infection with HIV and the development of symptoms. However, currently there is no cure for HIV infection or AIDS and no vaccine to prevent infection, although this is a field of intense study by biomedical scientists.

AIDS

AIDS is not a single disease but a collection of symptoms and diseases. It is the result of years of damage to the immune system by HIV. AIDS is diagnosed when helper T cells fall to a very low level and the infected person develops one or more opportunistic diseases.

Opportunistic diseases are infections and tumors that are rare in people with a healthy immune system but common in immunodeficient people. Opportunistic diseases include pneumocystis pneumonia and Kaposi's sarcoma, a type of cancer. The diseases are called opportunistic because they take advantage of the "opportunity" to infect a person with a damaged immune system that can't fight back. Opportunistic diseases are often the direct cause of death of people with AIDS.

AIDS was first identified in 1981. Since then it has killed more than 25 million people worldwide, many of them children. The hardest hit region is sub-Saharan Africa, where antiviral medications are least available. The worldwide economic toll of AIDS is also enormous.

Lesson Summary

- Allergies occur when the immune system makes an inflammatory response to a harmless antigen, called an allergen.
- Autoimmune diseases occur when the immune system fails to distinguish self from nonself and attacks the body's own cells.
- In an immunodeficiency disease, the immune system does not work normally and cannot defend the body.
- HIV is a virus that attacks cells of the immune system and eventually causes AIDS. It is the chief cause of immunodeficiency in the world today.

Review Questions

1. Describe anaphylaxis.
2. What is an autoimmune disease?
3. List three possible causes of acquired immunodeficiency.
4. Name two ways HIV can be transmitted.
5. Assume that you touch poison sumac and still have not developed a rash 12 hours later. Can you safely assume you are not allergic to the plant? Why or why not?
6. Rheumatic fever is caused by a virus that has antigens similar to molecules in human heart tissues. When the immune system attacks the virus, it also attacks the heart.

What type of immune system disease is rheumatic fever? Explain your answer.

7. Draw a timeline to show the progression of an untreated HIV infection. Show how the numbers of HIV copies and helper T cells change through time.
8. Why are opportunistic infections a sign of immunodeficiency?

Further Reading / Supplemental Links

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Vocabulary

acquired immunodeficiency Immunodeficiency that occurs when immune function declines in a person who was born with a normal immune system.

AIDS Acquired immune deficiency syndrome; a late stage in the progression of an HIV infection.

allergen Any antigen that causes an allergic reaction.

allergic rhinitis A common immediate hypersensitivity reaction; affects mainly mucous membranes lining the nose; often called hay fever.

allergy A disease in which the immune system makes an inflammatory response to a harmless antigen.

anaphylaxis An allergic response in which there is a sudden, massive release of histamines throughout the body. This causes collapse of the circulatory system and severe constriction of the breathing passages. Without emergency treatment, anaphylaxis is likely to be fatal.

antihistamines Drugs that reduce or eliminate the effects of histamines.

autoimmune diseases Diseases that occur when the immune system fails to recognize the body's own molecules as self and attacks the body's cells as though they were foreign invaders.

delayed hypersensitivity reaction When an antigen causes allergy symptoms hours or days after exposure.

epinephrine The "fight-or-flight" hormone that your adrenal glands normally produce when you are in danger; suppresses non-emergency body processes, including the immune response.

HIV The human immunodeficiency virus, the virus that causes AIDS.

immediate hypersensitivity reaction When exposure to an antigen causes immediate allergy symptoms.

immunodeficiency Occurs when one or more components of the immune system are not working normally; as a result, the ability of the immune system to respond to pathogens and other threats is decreased.

molecular mimicry Occurs when a person is infected with pathogens bearing antigens similar to the person's own molecules; when the immune system mounts an attack against the pathogens, it also attacks body cells with the similar.

opportunistic diseases Infections and tumors that are rare in people with a healthy immune system but common in immunodeficient people; includes pneumocystis pneumonia and Kaposi's sarcoma, a type of cancer.

Points to Consider

You read in this lesson that some types of cancer attack cells of the immune system and cause immunodeficiency. Cancer has previously been described as resulting from a loss of regulation of the cell cycle.

- Why do you think immunodeficiency may lead to some cancers?
- Can you think of a relationship between pathogens, the immune system, and the development of cancer?

24.4 Lesson 24.4: Environmental Problems and Human Health

Lesson Objectives

- Explain how carcinogens cause cancer and list ways that cancer can be treated or prevented.
- Identify causes of air pollution and describe how air pollution affects human health.
- Define bioterrorism and explain how bioterrorism threatens human health.

Introduction

Cancer is one of many human diseases that can be caused by environmental problems. For example, air pollution may increase the risk of lung cancer. It can also cause or worsen asthma, cardiovascular diseases, and other health problems. Bioterrorism is another potential threat to human health. It may lead to severe environmental problems that have the potential to poison large numbers of people or cause epidemics of deadly diseases.

Carcinogens and Cancer

A carcinogen is anything that can cause cancer. Cancer is a disease in which abnormal body cells divide of control. Most carcinogens cause cancer by inducing mutations.

Carcinogens

Carcinogens may be pathogens, chemical substances, or radiation. Carcinogens often occur in nature. For example, some viruses are important carcinogens, causing as many as 15 percent of all human cancers. Different viruses cause different cancers. The human papilloma virus (HPV) is the main cause of cancer of the cervix in females. The hepatitis B virus can cause liver cancer, and the Epstein-Barr virus can cause cancer of the lymph nodes.

Other natural carcinogens include ultraviolet (UV) radiation from the sun. UV radiation is the leading cause of skin cancer. Radon is a natural radioactive gas that seeps into buildings from the ground. Exposure to radon can cause lung cancer. Asbestos can also cause lung cancer. Asbestos is a mineral previously used for insulation and many other purposes. Today, it is largely banned because of its link to cancer.

Humans are exposed to many artificial carcinogens in the environment, including those in tobacco smoke. In fact, tobacco smoke may be the key source of human carcinogen exposure. It contains dozens of carcinogens including nicotine and formaldehyde, which is used to

preserve dead bodies. As you will read below, other pollutants in the air can cause cancer as well.

Other artificial carcinogens are or were found in foods. Some food additives, such as certain food dyes, have proven to be carcinogens. Cooking foods at very high temperatures also causes carcinogens to form. For example, a carcinogen called acrylamide forms when carbohydrates are cooked at very high temperatures. It is found in foods such as French fries and potato chips. Barbecued or broiled meats also contain several carcinogens.

How Cancer Occurs

Carcinogens generally cause cancer by inducing mutations in genes that control cell division or other aspects of the cell cycle. The mutations typically occur in two types of genes: tumor-suppressor genes and proto-oncogenes (see chapter titled *Molecular Genetics*). Briefly:

- Tumor-suppressor genes are genes that normally repair damaged DNA or prevent cells with badly damaged DNA from dividing (**Figure A** 24.14). If mutations occur in these genes, they may no longer be able to prevent cells with damaged DNA from dividing (**Figure B** 24.14).
- Proto-oncogenes are genes that normally help regulate cell division. Mutations can turn them into oncogenes. Oncogenes are abnormal genes that stimulate the division of cells with damaged DNA.

Cells that divide uncontrollably form a tumor. A tumor is an abnormal mass of tissue. Tumors may be benign or malignant. Benign tumors remain localized and generally do not harm health. Malignant tumors are cancer. There are no limits on their growth, so they can invade and damage neighboring tissues. Cells from malignant tumors can also break away from the tumor, enter the circulation, and start growing in another part of the body. This is called metastasis.

Types of Cancer

Cancer is usually classified according to the type of tissue where the cancer begins. Common types of cancer include:

- **Carcinoma**: tumor of epithelial tissues, such as lung tissue.
- **Sarcoma**: tumor of connective tissues, such as bone.
- **Lymphoma**: tumor of lymphatic cells, such as T cells.

Specific cancers are generally named for the organs where the cancers begin. Relatively common cancers include lung, prostate, bladder, and breast cancers. These and several

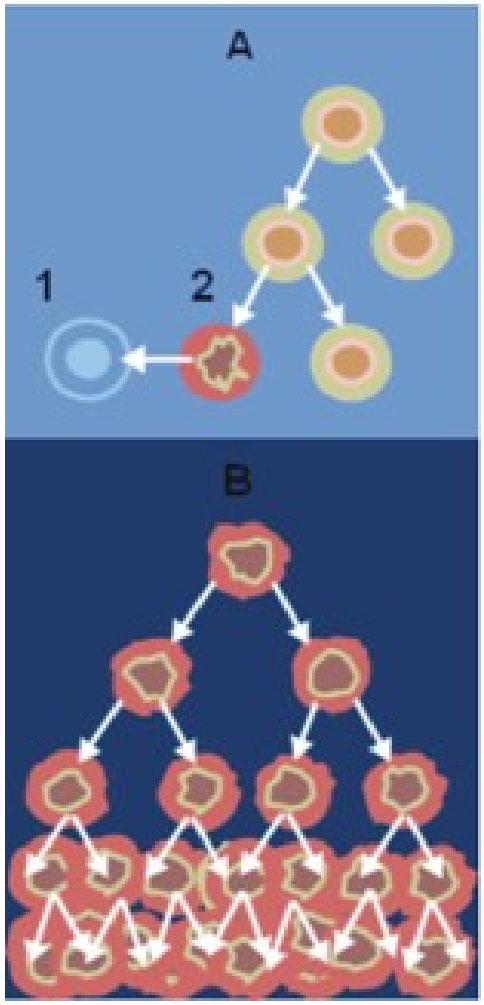

Figure 24.14: A cell with damaged DNA normally is not allowed to divide, so the damage is not passed on to other cells. If a cell with damaged DNA is allowed to divide, it results in many more damaged cells.

other cancers are listed in the **Table** 24.2. The figure shows which cancers are most common and which cause the most deaths in U.S. adults.

Table 24.2: **Common Cancers among Adult Males and Females in the United States**

Adult Males		Adult Females	
Most Common Cancers (percent of all cancers)	Most Common Causes of Cancer Deaths (percent of all cancer deaths)	Most Common Cancers (percent of all cancers)	Most Common Causes of Cancer Deaths (percent of all cancer deaths)
Prostate cancer(33%)	Lung cancer(31%)	Breast cancer(32%)	Lung cancer(27%)
Lung cancer(13%)	Prostate cancer(10%)	Lung cancer(12%)	Breast cancer(15%)
Colorectal cancer(10%)	Colorectal cancer(10%)	Colorectal cancer(11%)	Colorectal cancer(10%)
Bladder cancer(7%)	Pancreatic cancer(5%)	Endometrial cancer(6%)	Ovarian cancer(6%)

(*Source:* http://en.wikipedia.org/wiki/Cancer, *License:* Creative Commons)

Cancer can also occur in children and teens, but it is rare. Most childhood cancers occur during the first year of life. The most common type of infant cancer is leukemia. It makes up about 30 percent of cancers at this age. With prompt treatment, there is a good chance that an infant with cancer will survive.

Cancer Treatment and Prevention

Most cancers can be treated and some can be cured. The general goal of treatment is to remove the tumor without damaging the rest of the body. Cancer may be treated with a combination of surgery, chemotherapy, and/or radiation. In the past, chemotherapy drugs caused serious side effects. Many of today's chemotherapy drugs target specific molecules in tumors. This reduces damage to normal body cells and causes fewer side effects.

The outcome of cancer treatment depends on factors such as the type of cancer and its stage. The stage of cancer refers to the extent to which the cancer has developed. Generally, early diagnosis and treatment lead to the best chances of survival. That's why it's important for people to be aware of the following warning signs of cancer:

- A change in bowel or bladder habits
- A sore that does not heal
- Unusual bleeding or discharge from any place
- A lump in the breast or other parts of the body
- Chronic indigestion or difficulty in swallowing

- Obvious changes in a wart or mole
- Persistent coughing or hoarseness

Having warning signs of cancer does not mean that you have cancer, but you should see a doctor to be sure. Getting recommended tests for particular cancers, such as colonoscopies for colon cancer, can also help detect cancers early, when chances of a cure are greatest.

Many cancers can be prevented, or at least their risk can be reduced. You can help reduce your risk of cancer by avoiding specific carcinogens and maintaining a healthy lifestyle. Carcinogens you can avoid or limit your exposure to include tobacco smoke, sexually transmitted viruses, improperly cooked foods, and UV radiation. Other lifestyle choices you can make to reduce your risk of cancer include being physically active, eating a low-fat diet, and maintaining a normal weight.

Air Pollution and Illness

An estimated 4.6 million people die each year because of air pollution. Worldwide, air pollution causes more deaths than traffic accidents do. Air pollution harms the respiratory and cardiovascular systems. Both outdoor and indoor air can be polluted and contribute to illness and death.

Outdoor Air Pollution

The concentration of pollutants in outdoor air is indicated by the Air Quality Index. The Air Quality Index (AQI) is a measure of certain pollutants in the air in a given location. The health risks associated with different values of the AQI are shown in the **Table** 24.3 . When the AQI is high, you should limit the time you spend outdoors, especially the time you spend exercising. Avoiding exposure to air pollution can help limit its impact on your health. As you can see from **Table** 24.3, people with certain health problems, including asthma, need to be even more careful about limiting their exposure to air pollution.

Table 24.3: **Air Quality and Health Risk**

Air Quality Index(AQI)	Quality of Air in Terms of Human Health
0–50	Good
51–100	Moderate
101–150	Unhealthy for sensitive groups[1]
151–200	Unhealthy for everyone
201–300	Very unhealthy
301–500	Hazardous

[1] Sensitive groups include people with asthma, heart disease, or other diseases worsened by air pollution.

(*Source:* http://en.wikipedia.org/wiki/Air_Quality_Index, *License:* Creative Commons)

AQI reports to the public generally refer to levels of ground-level ozone and particulates. Ozone is a gas that forms close to the ground when high concentrations of air pollutants are heated by sunlight. Ozone damages both respiratory and cardiovascular systems. For example, it can cause asthma and decrease lung function. It can also convert cholesterol in arteries to plaque, causing cardiovascular disease. In addition, ozone may increase inflammation, which is a symptom of many diseases.

Particulates are tiny particles of solids or liquids suspended in the air. The most concentrated particulate pollution tends to be in the air over densely populated metropolitan areas in developing countries. The primary cause is the burning of fossil fuels by motor vehicles and factories. Particulates settle in airways and lungs and damage the respiratory tract. They can cause asthma and lung cancer. Extremely small particulates may pass through the lungs to the bloodstream and contribute to plaque formation in arteries.

Indoor Air Pollution

Indoor air quality refers to pollutants in the air inside buildings. Indoor air may be more polluted than outdoor air, although with different pollutants. Typical pollutants in indoor air include allergens, mold, bacteria, carbon monoxide, and radon.

Mold and bacteria can be allergens and also cause respiratory system infections. For example, a type of pneumonia, known as Legionnaire's disease, is caused by bacteria that can spread through air conditioning systems. The disease is not common, but it kills many of the people who contract it.

Carbon monoxide is a gas produced by cars, furnaces, and other devices that burn fuel. It replaces oxygen in the blood and quickly leads to death. Initial symptoms of carbon monoxide poisoning include headache, listlessness, and other flu-like symptoms. Loss of consciousness and death can occur within hours. An estimated 40,000 Americans annually seek medical attention for carbon monoxide poisoning. It is also the most common type of fatal poisoning in the U.S. Carbon monoxide is colorless and odorless, but it can be detected with carbon monoxide detectors like the one in **Figure** 24.15.

Sick building syndrome (SBS) is a combination of symptoms associated with working in a particular building, typically an office building. It is most common in new and remodeled buildings. It is usually caused by inadequate ventilation. Chemicals released by new building materials may also contribute to the poor air quality. Generally, conditions improve by increasing ventilation. Symptoms of SBS vary widely. They may include headaches, eye irritation, dry cough, dizziness, and asthma.

Figure 24.15: Home carbon monoxide detector

Bioterrorism

Bioterrorism is terrorism by intentional release or spread of pathogens. As shown in **Tables** 24.4, 24.5, and 24.6, pathogens used in bioterrorism may include bacteria, viruses, or toxins. Toxins are poisons produced by organisms such as bacteria. The agents may be naturally occurring pathogens or pathogens that have been modified by humans to make them more effective agents of bioterrorism. The agents can spread in a variety of ways, including through air, food, water, direct contact, or cuts in the skin. They have the potential to cause epidemics of deadly human diseases.

Table 24.4: **Classification of Category A Bioterrorism Agents Based Upon Threat to Public Health**

Agent	Type of Pathogen	Mode of Transmission
Anthrax	Bacteria	Air, food, cuts in skin
Smallpox	Virus	Air, direct contact
Botulinum	Toxin	Food, cuts in skin

Table 24.5: **Classification of Category B Bioterrorism Agents Based Upon Threat to Public Health**

Agent	Type of Pathogen	Mode of Transmission
Brucellosis	Bacteria	Milk, direct contact
Ricin	Toxin	Air, food, water
Cholera	Bacteria	Food, water

Table 24.6: **Classification of Category C Bioterrorism Agents Based Upon Threat to Public Health**

Agent	Type of Pathogen	Mode of Transmission
Hantavirus	Virus	Air
Tuberculosis	Bacteria	Air

Agents of Bioterrorism

Bioterrorism agents are classified on the basis of their threat to public health, as shown in the tables above. Category A agents (**Table** 24.4) include anthrax and smallpox. Agents in this category pose the greatest threat. They spread easily and cause serious illness or death. Category B agents (**Table** 24.5) are considered less of a threat. They do not spread as easily

and are less likely to cause death. Category C agents (**Table** 24.6) are pathogens that are likely to be engineered for bioterrorism in the future. They are easy to produce and have the potential to cause serious illness or death.

Recent Bioterrorism Incidents

Two recent bioterrorism incidents in the U.S. received a great deal of media attention. They heightened public awareness of the threat of bioterrorism. In 2001, letters containing anthrax spores were mailed to several news media offices and two U.S. Senate offices. A total of 22 people were infected, and 5 of them died of anthrax. In 2003, deadly ricin toxin was detected in a letter intended for the White House. The letter was intercepted at a mail-handling facility off White House grounds. Fortunately, the ricin did not cause illness or death.

Lesson Summary

- Carcinogens cause cancer by inducing mutations in genes that normally control cell division or other aspects of the cell cycle.
- Both indoor and outdoor air may contain pollutants that can cause human illness and death.
- In bioterrorism, pathogens are intentionally released or spread and have the potential to cause disease epidemics.

Review Questions

1. What is a carcinogen?
2. How do carcinogens cause cancer?
3. Identify three ways cancer can be treated.
4. List four warning signs of cancer.
5. How can you use the Air Quality Index to protect your health from air pollution?
6. The bacterium that causes plague is classified as a Category A bioterrorism agent. What can you conclude about the bacterium from this classification?
7. Explain why ozone is usually a worse problem in the summer than in the winter in North America.
8. Compare and contrast pollutants in indoor and outdoor air, including their effects on human health.

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Vocabulary

air quality index (AQI) A measure of certain pollutants in the air in a given location.

bioterrorism Terrorism by intentional release or spread of pathogens.

cancer A disease in which abnormal body cells divide of control.

carbon monoxide A gas produced by cars, furnaces, and other devices that burn fuel; replaces oxygen in the blood and quickly leads to death.

carcinogen Anything that can cause cancer; may be pathogens, chemical substances, or radiation.

carcinoma A tumor of epithelial tissues, such as lung tissue.

lymphoma A tumor of lymphatic cells, such as T cells.

oncogenes Abnormal genes that stimulate the division of cells with damaged DNA.

ozone A gas that forms close to the ground when high concentrations of air pollutants are heated by sunlight.

particulates Tiny particles of solids or liquids suspended in the air; primarily formed by the burning of fossil fuels by motor vehicles and factories.

proto-oncogenes Genes that normally help regulate cell division.

sarcoma A tumor of connective tissues, such as bone.

sick building syndrome (SBS) A combination of symptoms associated with working in a particular building, typically an office building.

tumor An abnormal mass of tissue.

tumor-suppressor genes Genes that normally repair damaged DNA or prevent cells with badly damaged DNA from dividing.

Points to Consider

High levels of certain hormones can increase the risk of some types of cancer. For example, high levels of estrogen can increase the risk of breast cancer. Estrogen is a female sex hormone.

- What are sex hormones?
- How do sex hormones normally affect the body?
- How are male and female sex hormones different?

Image Sources

(1) CK-12 Foundation. http://commons.wikimedia.org/wiki/File:Cytotoxic_T_cell.jpg. Public Domain.

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(4) http://upload.wikimedia.org/wikipedia/en/d/d2/DQ_Illustration.PNG. Creative Commons.

(5) http://commons.wikimedia.org/wiki/File:Normal_cancer_cell_division_from_NIH.png. Public Domain.

(6) *http://en.wikipedia.org/wiki/Image:Herpes_simpex_virus.jpg* *http://en.wikipedia.org/wiki/Image:Amanita_phalloides_1.jpg* *http://upload.wikimedia.org/wikipedia/commons/0/08/Giardia_lamblia_SEM_8698_lores.jpg*. Creative Commons.

(7) *Magnified image of a macrophage.*. CC-BY-SA.

(8) *Human lymphatic system.*. Creative Commons.

(9) http://en.wikipedia.org/wiki/Image:Antibody.svg. Public Domain.

(10) *http://en.wikipedia.org/wiki/Image:PBNeutrophil.jpg* *http://upload.wikimedia.org/wikipedia/en/1/1b/Eosinophil.jpg* *http://en.wikipedia.org/wiki/Image:PBBasophil.jpg* *http://en.wikipedia.org/wiki/Image:Lymphocyte2.jpg*. Creative Commons.

(11) *Phagocytosis by a macrophage.*. Creative Commons.

(12) http://commons.wikimedia.org/wiki/File:Poisonivyrash.jpg. Public Domain.

(13) http://upload.wikimedia.org/wikipedia/en/d/d2/Ambrosia_5977.jpg. Creative Commons.

(14) *Home carbon monoxide detector*. Creative Commons.

(15) http://commons.wikimedia.org/wiki/File:Hiv-timecourse.png. GNU-FDL.

Chapter 25

Reproductive System and Human Development

25.1 Lesson 25.1: Male Reproductive System

Lesson Objectives

- Explain how the male reproductive system develops before birth and matures during puberty.
- Identify structures of the male reproductive system and their functions.
- Describe how sperm are produced and how they leave the body.

Introduction

The male reproductive system is a collection of organs and other structures in the pelvic region. Most of the structures are located outside the body. The male reproductive system has two major functions: producing sperm and secreting male sex hormones. **Sperm** are male gametes, or sex cells, which are necessary for reproduction. During puberty, a boy develops into a sexually mature male, capable of producing sperm and reproducing.

Sexual Development in Males

The main visible differences between boys and girls at birth are their reproductive organs. Of course, there are other differences between boys and girls at birth, but in this chapter, the focus is on their reproductive systems. As different as the male and female reproductive systems are at birth, they start out relatively similar. Before birth, the expression of genes on the male Y-chromosome brings about the differences.

Development Before Birth

In the first few weeks of life, male and female embryos are essentially the same, except for their chromosomes. Females have two X chromosomes, and males have an X and a Y chromosome. In male embryos, genes on the Y chromosome lead to the synthesis of testosterone. This begins around the sixth week of life.

Testosterone is a masculinizing hormone and the chief sex hormone in males. Testosterone stimulates the embryo's reproductive organs to develop into male organs. For example, because of testosterone, the embryo develops testes instead of ovaries, which are female organs you will read about in Lesson 25.2.

All the reproductive organs are present by birth. However, they are immature and unable to function. The reproductive organs grow very little during childhood and do not mature until puberty.

Puberty and Its Changes

Puberty is the period during which humans become sexually mature. In the United States, boys generally begin puberty at about age 12 years. Puberty starts when the hypothalamus, a gland in the brain, stimulates the nearby pituitary gland to secrete hormones that target the testes. The main pituitary hormone responsible for puberty in males is luteinizing hormone (LH). It stimulates the testes to produce testosterone. Testosterone promotes protein synthesis and growth. It brings about most of the physical changes of puberty, including the changes outlined in **Table** 25.1.

Table 25.1: **Changes in Males During Puberty**

Changes in Reproductive Organs	
Testes grow larger	Penis grows longer
Other reproductive structures grow	Sperm production begins
Other Physical Changes	
Pubic hair grows	Facial and body hair grow
Bone density increases	Long bones grow
Muscle mass and strength increase	Bones in face grow
Adam's apple grows	Apocrine sweat glands develop
Shoulders widen	Voice deepens

Cells that are targeted by testosterone are those that have testosterone receptors. Receptors are molecules in or on cells that bind to specific hormones. Testosterone receptors are on the nucleus of cells. After binding to testosterone, they enter the nucleus, where they bind to specific DNA sequences and regulate gene transcription.

Some of the changes in **Table** 25.1 involve maturation of the reproductive organs, including the penis. Traits such as adult penis size are called **primary sex characteristics**. Other changes, such as growth of pubic hair, are not directly related to reproduction. Characteristics of mature males such as pubic hair are called **secondary sex characteristics**.

Adolescent Growth Spurt

Another obvious change that occurs during puberty is rapid growth in height. This is called the adolescent growth spurt. In males, the rate of growth usually starts to increase relatively early in puberty. At its peak rate, growth in height is typically about 10 centimeters per year. Growth generally remains rapid for several years. Growth and development of muscles occur toward the end of the growth spurt in height. Muscles may continue to develop and gain strength after growth in height is finished.

Timing of Puberty

The ages at which particular changes of puberty occur differ from one person to another. However, the changes generally occur in the same sequence for most males. The sequence in which some of the more obvious changes occur is represented by the following stages:

Stage 1—The scrotum and testes grow larger.
Stage 2—The penis becomes longer; pubic hair appears.
Stage 3—Facial and underarm hair appear; the voice deepens.

In the U.S., the average boy begins Stage 1 of puberty at age 11.5 years. He begins the growth spurt in height by the second year of puberty, develops the ability to produce sperm a few years later, and continues to grow in height until age 17.5 years. Overall, he spends about six years going through puberty.

Depending on the genes he inherits, his diet, and many other factors, a boy may go through puberty a couple of years earlier or later than the average. This is usually normal, and early and late maturers generally have nothing to worry about. Nonetheless, a boy who is concerned that he is not developing normally should talk with his doctor.

Male Reproductive Organs

Penis, Testes, and Epididymis

The **penis** is an external genital organ with a long shaft and enlarged tip. It contains tissues that can fill with blood and cause an erection, which is stiffening and enlarging of the penis.

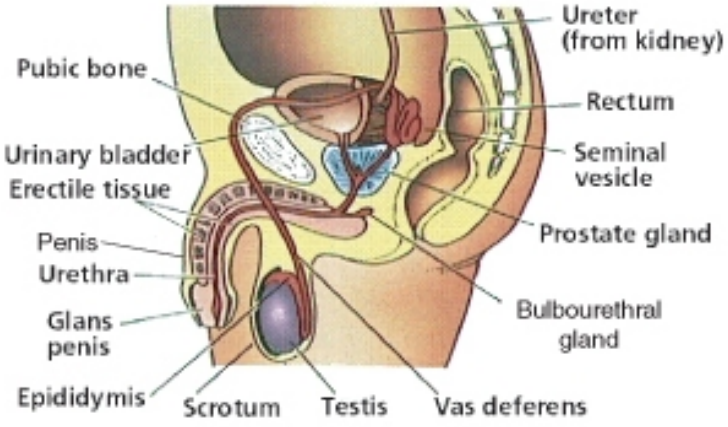


Figure 25.1: shows the male reproductive system. The main organs are the penis, testes, and epididymis. Several ducts and glands are also parts of the male reproductive system.

A duct called the urethra passes through the penis. Sperm pass out of the body through the urethra. (During urination, the urethra carries urine from the bladder.)

The **testes** (singular, testis) are located in the scrotum, which is a sac of skin between the upper thighs. By hanging away from the body, the testes keep sperm at a temperature lower than normal body temperature. The lower temperature is needed for sperm production.

Each testis contains more than 90 meters of tiny, tightly-packed tubes called **seminiferous tubules**. They are the functional units of the testes, where sperm are produced and testosterone is secreted. A cross-section of a seminiferous tubule is shown in **Figure** 25.2. The tubule is lined with spermatogonia and Sertoli cells. Spermatogonia are sperm-producing cells that you will read more about below. Sertoli cells help protect and nourish developing sperm.

In between the seminiferous tubules in the testes are interstitial cells, also called Cells of Leydig. These cells secrete testosterone. A high concentration of testosterone is necessary for sperm production. Testosterone is also needed throughout a man's life to maintain his secondary sex characteristics.

The seminiferous tubules join together to form the epididymis. The **epididymis** is a coiled tube about 6 meters long lying atop the testes inside the scrotum (**Figure** 25.1). Its functions are to help sperm mature and to store mature sperm until they leave the body.

Ducts and Glands

In addition to these organs, the male reproductive system consists of a series of ducts and glands. These are also shown in **Figure** 25.1.

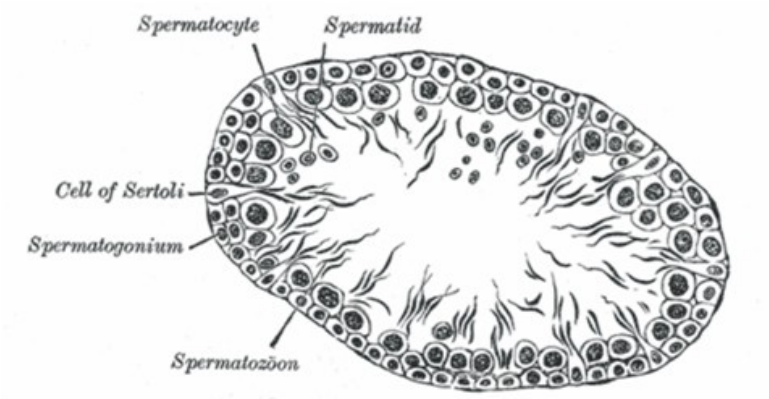


Figure 25.2: This drawing shows a cross-section of a seminiferous tubule. Spermatogonia line the inside of the tubule, interrupted here and there by Sertoli cells. Spermatocytes, which are produced by spermatogonia, form the next layer of cells. Spermatids, which are produced by spermatocytes, form a third layer of cells.

- Ducts include the vas deferens and ejaculatory ducts. They transport sperm from the epididymis to the urethra in the penis.
- Glands include the seminal vesicles, prostate gland, and bulbourethral glands. They secrete substances that become part of semen.

Semen is the fluid that is ejaculated from the urethra. Semen contains secretions from the glands as well as sperm. The secretions control pH and provide the sperm with nutrients for energy.

Production and Delivery of Sperm

A sexually mature male typically produces several hundred million sperm per day. Sperm production usually continues uninterrupted until death, although the number and quality of sperm decline during later adulthood.

Spermatogenesis

Spermatogenesis is the process of producing mature sperm. Sperm are haploid cells, meaning they have half the number of chromosomes as other cells of the body, which are diploid cells. Sperm must be haploid in order for normal sexual reproduction to occur. During reproduction, a sperm unites with another cell, called an egg. This is called **fertilization**. Unless both sperm and egg are haploid, the resulting offspring will not have the diploid number of chromosomes (see chapter titled *Cell Division and Reproduction*).

Sperm are produced in the seminiferous tubules of the testes and finish maturing in the

epididymis. The entire process takes about 9 to 10 weeks. As shown in **Table** 25.2, the production of sperm occurs in several steps, each involving a different type of cell and process.

Spermatogenesis begins when a spermatogonium with the diploid number of chromosomes undergoes mitosis to form primary spermatocytes, also with the diploid number. It proceeds as a primary spermatocyte undergoes the first cell division of meiosis to form secondary spermatocytes with the haploid number of chromosomes. A secondary spermatocyte undergoes the second meiotic cell division to form haploid spermatids. Spermatids mature into sperm, which are also haploid.

Table 25.2: **Spermatogenesis and Cell Division**

Type of Cell	Number of Chromosomes	Process
Spermatogonium	Diploid	Mitosis
Primary Spermatocyte	Diploid	Meiosis 1
Secondary Spermatocyte	Haploid	Meiosis 2
Spermatid	Haploid	Maturation
Spermatozoon (sperm)	Haploid	Fertilization

Spermatogonia, which line the seminiferous tubules in the testes, are diploid cells. They begin the process of spermatogenesis when they divide by mitosis to produce cells called primary spermatocytes, which are also diploid cells. Some spermatogonia divide just to produce copies of themselves. This ensures a constant supply of spermatogonia for future sperm production.

Primary spermatocytes go through the first cell division of meiosis to produce secondary spermatocytes. These are haploid cells. Secondary spermatocytes then quickly complete the meiotic division to become spermatids, which are also haploid cells.

Spermatids slowly mature into sperm, like the one shown in **Figure** 25.3. Among other changes, they lose excess cytoplasm from the head and grow a tail. The tail is a flagellum that lets them move by rotating like a propeller. The acrosome that covers part of the head produces digestive enzymes that help the head penetrate an egg. The mitochondria in the connecting piece produce energy that the sperm needs to "swim" through the female reproductive tract to reach an egg. However, sperm do not develop the ability to move until they complete their maturation in the epididymis. It takes sperm four to six weeks to travel through the epididymis and become fully mature. After they mature, they remain in the epididymis until they leave the body.

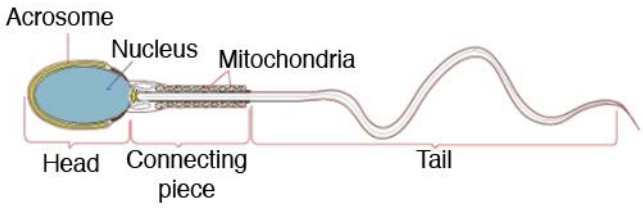


Figure 25.3: A mature sperm cell has several structures that help it reach and penetrate an egg. These structures include the acrosome, mitochondria, and tail. The nucleus, which makes up most of the head, carries copies of the father's chromosomes.

Ejaculation

In order for reproduction to take place, sperm must leave the reproductive system. Sperm are released from the body during **ejaculation**. About 200 to 500 million sperm are released with each ejaculation. Ejaculation occurs when rhythmic muscular movements of the vas deferens propel sperm from the epididymis. The sperm are forced through the vas deferens and ejaculatory ducts and out of the body through the urethra. As sperm travel through the ducts, they mix with fluids from the seminal vesicles, prostate gland, and bulbourethral glands to form semen.

Lesson Summary

- The male reproductive system forms before birth but does not become capable of reproduction until it matures during puberty.
- The male reproductive system includes organs and other structures that produce sperm and deliver sperm and secrete testosterone.
- Sperm are produced in the testes in the process of spermatogenesis and leave the body through the penis during ejaculation.

Review Questions

1. What are the two major functions of the male reproductive system?
2. List four physical changes that occur in males during puberty.
3. Name two male reproductive organs and identify their functions.
4. Describe how sperm leave the body.
5. Sexual dimorphism refers to differences between males and females of the same species. Based on what you read in this lesson, how does human sexual dimorphism change from birth to adulthood?

6. If a man did not have an epididymis, how would this affect his ability to produce mature sperm?
7. Make a flow chart showing the steps of spermatogenesis. Indicate the cells and process involved at each step.
8. What are the roles of testosterone in the male reproductive system, from the embryo to old age?

Further Reading / Supplemental Links

- Stanley, Deborah, *Sexual Health Information for Teens*. Omnigraphics, 2003.
- Walker, Pam and Wood, Elaine, *Understanding the Human Body: The Reproductive System*. Lucent Books, 2002.
- http://en.wikibooks.org/wiki/Human_Physiology/The_male_reproductive_system
- http://www.kidshealth.org/parent/general/body_basics/male_reproductive.html
- http://www.kidshealth.org/teen/sexual_health/changing_body/male_repro.html
- http://www.medicalook.com/human_anatomy/systems/Male_Reproductive_System.html
- http://en.wikipedia.org

Vocabulary

acrosome Covers part of the sperm cell head; produces digestive enzymes that help the sperm head penetrate an egg.

adolescent growth spurt Rapid growth in height seen during puberty.

Cells of Leydig Cells that secrete testosterone, located in between the seminiferous tubules in the testes; are also known as interstitial cells.

epididymis A coiled tube about 6 meters long lying atop the testes inside the scrotum; helps sperm mature and stores mature sperm until they leave the body.

fertilization The uniting of a haploid sperm with a haploid egg.

luteinizing hormone The main pituitary hormone responsible for puberty in males; stimulates the testes to produce testosterone.

male reproductive system System with two major functions: producing sperm and secreting testosterone.

primary sex characteristics Traits of reproductive organs seen in mature adults that are directly related to reproduction.

puberty The period during which humans become sexually mature.

secondary sex characteristics Physical traits of mature adults which are not directly related to reproduction.

semen The fluid that is ejaculated from the urethra; contains sperm and secretions from the seminal vesicles, prostate gland, and bulbourethral glands.

seminiferous tubules The functional units of the testes, where sperm are produced and testosterone is secreted.

sertoli cells Help protect and nourish developing sperm, located in the seminiferous tubules.

sperm Male gametes, or sex cells, which are necessary for reproduction; haploid.

spermatogonia Sperm-producing cells, located in the seminiferous tubules; diploid.

spermatogenesis The process of producing mature sperm.

testosterone A masculinizing hormone and the chief sex hormone in males.

Points to Consider

- By the time they finish puberty, males have developed the traits of mature adults of their own sex. They differ from mature females in many ways. How do these differences between sexually mature males and females come about?
- What causes female to develop differently during puberty?
- When do girls begin puberty, what changes do they go through, and what hormones control the changes?

25.2 Lesson 25.2: Female Reproductive System

Lesson Objectives

- Explain how the female reproductive system develops before birth and matures during puberty.
- Identify structures of the female reproductive system and their functions.
- Describe how eggs are produced and how they are released from the ovaries.
- Sequence the events of the menstrual cycle, and explain how hormones control the cycle.

Introduction

The female reproductive system is a collection of organs and other structures located primarily in the pelvic region. Most of the structures are inside the body. The female reproductive system has several functions:

- producing eggs, which are female gametes
- secreting female sex hormones
- receiving sperm during sexual intercourse
- supporting the development of a fetus
- delivering a baby during birth
- breastfeeding a baby after birth

During puberty, a girl develops into a sexually mature woman, capable of producing eggs and reproducing.

Sexual Development in Females

As you read in Lesson 25.1, the main differences between boys and girls at birth are their reproductive organs. Unlike males, females are not influenced by the male sex hormone testosterone during embryonic and fetal development. This is because they lack a Y-chromosome. As a result, females do not develop male reproductive organs.

Development Before Birth

Unless an embryo is stimulated by testosterone, the reproductive organs develop into female organs, such as the ovaries and uterus. By the third month of fetal development, most of the internal female organs have formed. Immature **ova**, or eggs, also form in the ovary before birth. Whereas a male produces sperm throughout his lifetime (after puberty), a female produces all the eggs she will ever make before birth.

Like baby boys, baby girls are born with all their reproductive organs present but immature and unable to function. Female reproductive organs grow very little during childhood. They begin to grow rapidly and to mature during puberty.

Changes of Puberty

From Lesson 25.1, you know that puberty is the period during which humans become sexually mature. Puberty in girls differs from puberty in boys in several ways, including when it begins, how long it lasts, and the hormones involved. Girls begin puberty a year or two

earlier than boys, and they complete puberty in about four years instead of six. In females, the major sex hormone is **estrogen** rather than testosterone.

Puberty in girls starts when the hypothalamus in the brain stimulates the pituitary gland to secrete hormones that target the ovaries. The pituitary hormones are luteinizing hormone, or LH, and follicle-stimulating hormone, or FSH. These hormones stimulate the ovary to produce estrogen.

Estrogen has many functions that you will read more about below. During puberty, estrogen promotes growth and other physical changes in females. For example, estrogen stimulates growth of the breasts and uterus. It also stimulates development of bones and contributes to the adolescent growth spurt in height. These and several other changes in females during puberty are listed in **Table** 25.3:

Table 25.3: **Physical Changes in Females During Puberty**

Changes in Reproductive Organs	
Ovaries and follicles grow	Uterus grows and endometrium thickens
Other reproductive structures grow	Menstrual cycle begins
Other Physical Changes	
Breasts develop	Long bones grow and mature
Pubic hair grows	Underarm hair grows
Body fat increases	Apocrine sweat glands develop
Pelvis widens	

Some of the changes involve the maturation of organs, such as ovaries, that are necessary for reproduction. Mature reproductive organs are primary sex characteristics. Other changes, such as growth of pubic hair, lead to traits that are secondary sex characteristics. One of the most significant changes in females during puberty is menarche. **Menarche** is the beginning of menstruation, or monthly periods, which will be discussed later.

Adolescent Growth Spurt

Females go through an adolescent growth spurt in height as boys do. However, the growth spurt in girls starts a year or two earlier and ends about three years sooner. Girls also do not grow as rapidly during their peak growth rate. Although females start the growth spurt only 2 centimeters shorter than males, on average, by the time they stop growing females are an average of 10 centimeters shorter.

Timing of Puberty

The changes of puberty usually happen in the same order for most females. The first observable change is typically the beginning of breast development. This happens by age 10 years in the majority of girls in the U.S. The appearance of pubic hair usually occurs next, at age 10.5 years, on average. The growth spurt in height also usually begins during the first year of puberty. During the first two years of puberty, the ovaries and uterus gradually increase in size. Menarche occurs relatively late in puberty, typically between the ages of 12 and 13 years in U.S. girls. After menarche, a female generally keeps growing for another year or two and attains her adult height by an average age of 14.5 years.

As in males, there is a wide range of ages at which particular changes of female puberty normally occur. For example, menarche may occur as early as age 8 years or as late as age 16. Differences in age at menarche and other changes of puberty are due to both genetic factors and environmental factors, such as diet. A female who goes through puberty earlier or later than her peers may worry that she is not developing normally. Although such variation is usually normal, she should talk with her health care provider if she has concerns.

Female Reproductive Organs

The female reproductive system is shown in **Figure** 25.4. Only a few of the structures are external to the body. All the main reproductive organs are internal.

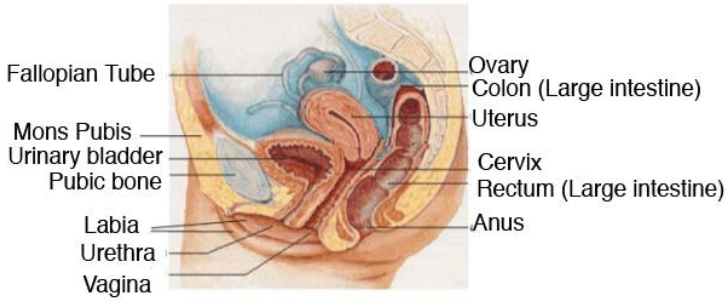


Figure 25.4: The female reproductive system.

External Organs

The external female reproductive structures are referred to collectively as the **vulva**. They include the labia and mons pubis. The labia are the "lips" of the vulva. They protect the vagina and urethra, both of which have openings in the vulva. The mons pubis consists of fatty tissue covering the pubic bone. It protects the pubic bone and vulva from injury.

Internal Organs

The internal female reproductive organs include the vagina, uterus, fallopian tubes, and ovaries. These organs are shown from the front, without any other structures blocking them, in **Figure** 25.5. This makes it easier to see the shape and size of the organs and where they are located relative to one another.

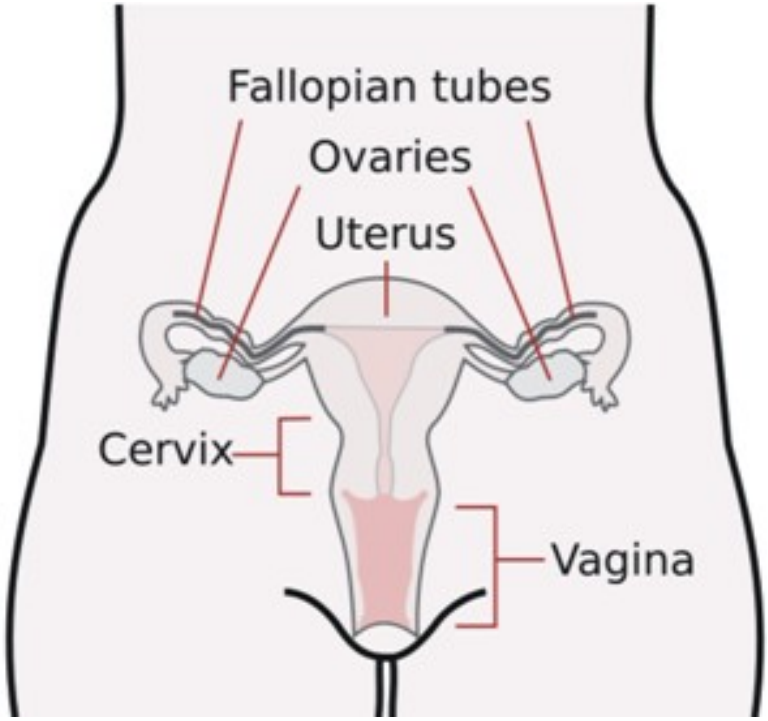


Figure 25.5: Internal female reproductive organs.

The **vagina** is a tube-like structure about 8 to 10 centimeters long. It begins at the vulva and extends to the uterus. It has muscular walls lined with mucous membranes. The vagina has two major reproductive functions. It receives sperm during sexual intercourse, and it provides a passageway for a baby to leave the mother's body during birth.

The **uterus** is a muscular organ about 7.5 centimeters long and 5 centimeters wide. It has a thick lining of tissues known as the endometrium. The lower, narrower end of the uterus is called the **cervix**. The uterus is where a fetus grows and develops until birth. During pregnancy, the uterus can expand dramatically to accommodate the growing baby. Muscular contractions of the uterus push the baby through the cervix during childbirth.

Extending from the upper corners of the uterus are the two **Fallopian tubes**. The tubes are about 7 to 14 centimeters long. Each tube reaches (but is not attached to) one of the ovaries. The ovary end of the tube has a fringelike structure (**Figure** 25.8) that moves with a wavelike motion.

The two **ovaries** are small, oval-shaped organs that lie on either side of the uterus. They are the egg-producing organs of the female reproductive system, and they contain hundreds of thousands of immature eggs. Each egg is located within a structure called a **follicle**. A follicle consists of the egg surrounded by special cells that protect the egg until puberty and then help the egg mature.

The Breasts

The breasts are considered secondary sex characteristics, rather than organs of reproduction. They are described here because of their role in nurturing an infant after birth. As shown in **Figure** 25.6, each breast contains mammary glands. The cells of mammary glands secrete milk, which drains into ducts leading to the nipple. A suckling baby squeezes the milk out of the ducts and through the nipple.

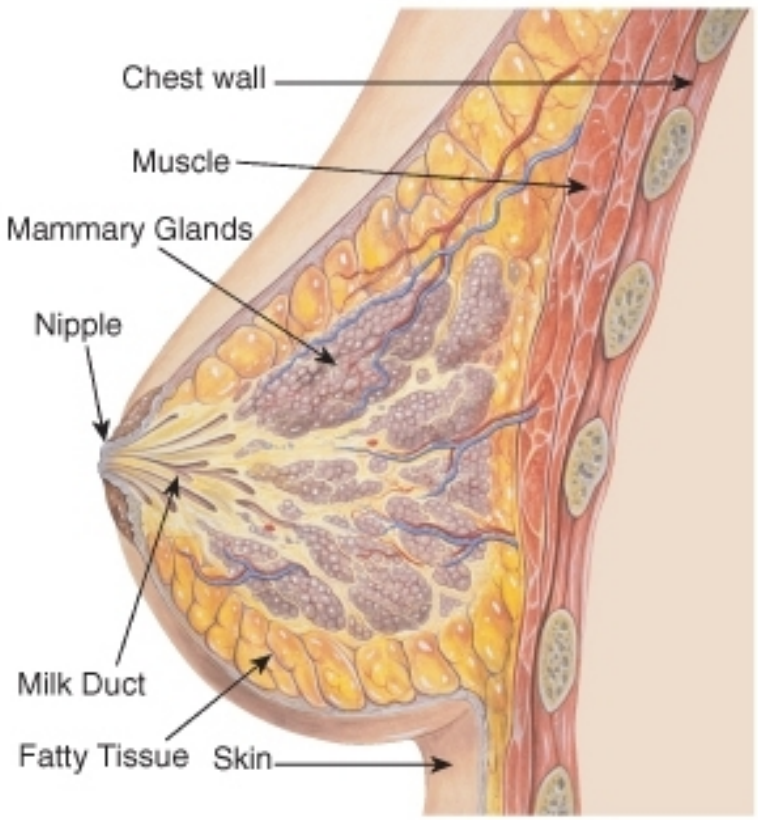


Figure 25.6: Cross-section of a human breast.

Egg Production

At birth, a female's ovaries contain all the eggs she will ever produce. However, the eggs do not start to mature until she enters puberty. After menarche, one egg typically matures each month throughout a female's adult years until she reaches middle adulthood.

Oogenesis

Oogenesis is the process of producing eggs in the ovary. Eggs are haploid cells, having half the number of chromosomes of other cells in the body, which are diploid cells. Like sperm, eggs must be haploid in order for sexual reproduction to result in diploid offspring. Like spermatogenesis, oogenesis occurs in several steps that involve different types of cells. The steps of oogenesis are listed in **Table** 25.4.

Oogenesis begins when an oogonium with the diploid number of chromosomes undergoes mitosis to form primary oocytes, also with the diploid number. It proceeds as a primary oocyte undergoes the first cell division of meiosis to form secondary oocytes with the haploid number of chromosomes. A secondary oocyte undergoes the second meiotic cell division to form a haploid ovum if it is fertilized by a sperm.

Table 25.4: **Oogenesis and Cell Division**

Type of Cell	Number of Chromosomes	Process
Oogonium	Diploid	Mitosis
Primary oocyte	Diploid	Meiosis 1
Secondary oocyte	Haploid	Meiosis 2
Ovum (mature egg)	Haploid	Fertilization

Oogenesis begins with **oogonia** (singular, oogonium), which are the immature eggs that form in the ovaries before birth. Oogonia are diploid cells and equivalent to spermatogonia in males. By about the fifth month of fetal development, the ovaries contain about seven million oogonia.

Over the next few months, oogonia undergo mitosis, forming cells called primary oocytes. Primary oocytes are also diploid cells. Before birth, primary oocytes begin the first division of meiosis, but they do not complete it until long after birth. At birth, the average female has about two million primary oocytes in her ovaries. Throughout childhood, the number of oocytes falls as they deteriorate and disappear. By puberty, there are only about 300,000 to 400,000 primary oocytes left in the average girl's ovaries.

Maturation of a Follicle

Beginning in puberty, each month one of the follicles starts to mature (**Figure** 25.7). The primary oocyte in the follicle resumes meiosis and divides to form a secondary oocyte and a smaller cell, called a polar body. Both the secondary oocyte and polar body are haploid cells. The secondary oocyte has most of the cytoplasm from the original cell and is much larger than the polar body. The polar body disintegrates and disappears from the ovary.

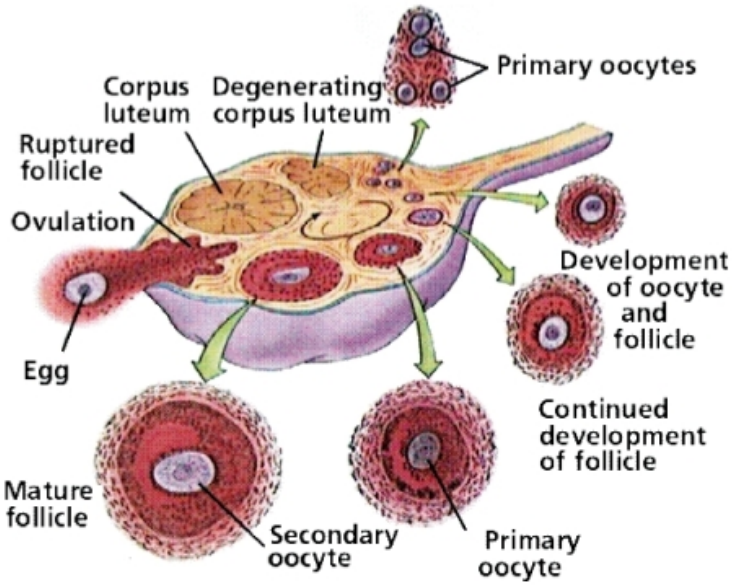


Figure 25.7: This diagram shows the monthly cycle the ovary goes through in a post-pubertal female. First, an oocyte and its surrounding follicle starts to mature. When the secondary oocyte is mature, it bursts from the follicle and ovary. Then the ruptured follicle develops into a corpus luteum, which produces progesterone. If the egg is not fertilized by a sperm, the corpus luteum degenerates and virtually disappears from the ovary.

Ovulation

Ovulation is the release of a secondary oocyte by the ovary. Ovulation occurs every 28 days, on average, in a sexually mature female, but may range normally from 24 to 36 days. As shown in **Figure** 25.7, during ovulation a secondary oocyte bursts out of its follicle and through the ovary wall to enter the abdominal cavity.

Each month only one of the ovaries matures a follicle and releases an egg. Which ovary matures a follicle in a given month? Scientists say that it appears to be random.

After the secondary oocyte leaves the ovary, it is swept into the Fallopian tube by the waving, fringelike end. This is illustrated in **Figure** 25.8. Tiny hairlike projections, called cilia, line

the tube and help move the oocyte through to the uterus. If the secondary oocyte is fertilized by a sperm as it is passing through the Fallopian tube, it divides to form a mature egg and a polar body, finishing meiosis. (As before, the polar body contains very little cytoplasm and disintegrates.) If the secondary oocyte is not fertilized, it passes into the uterus as an immature egg.

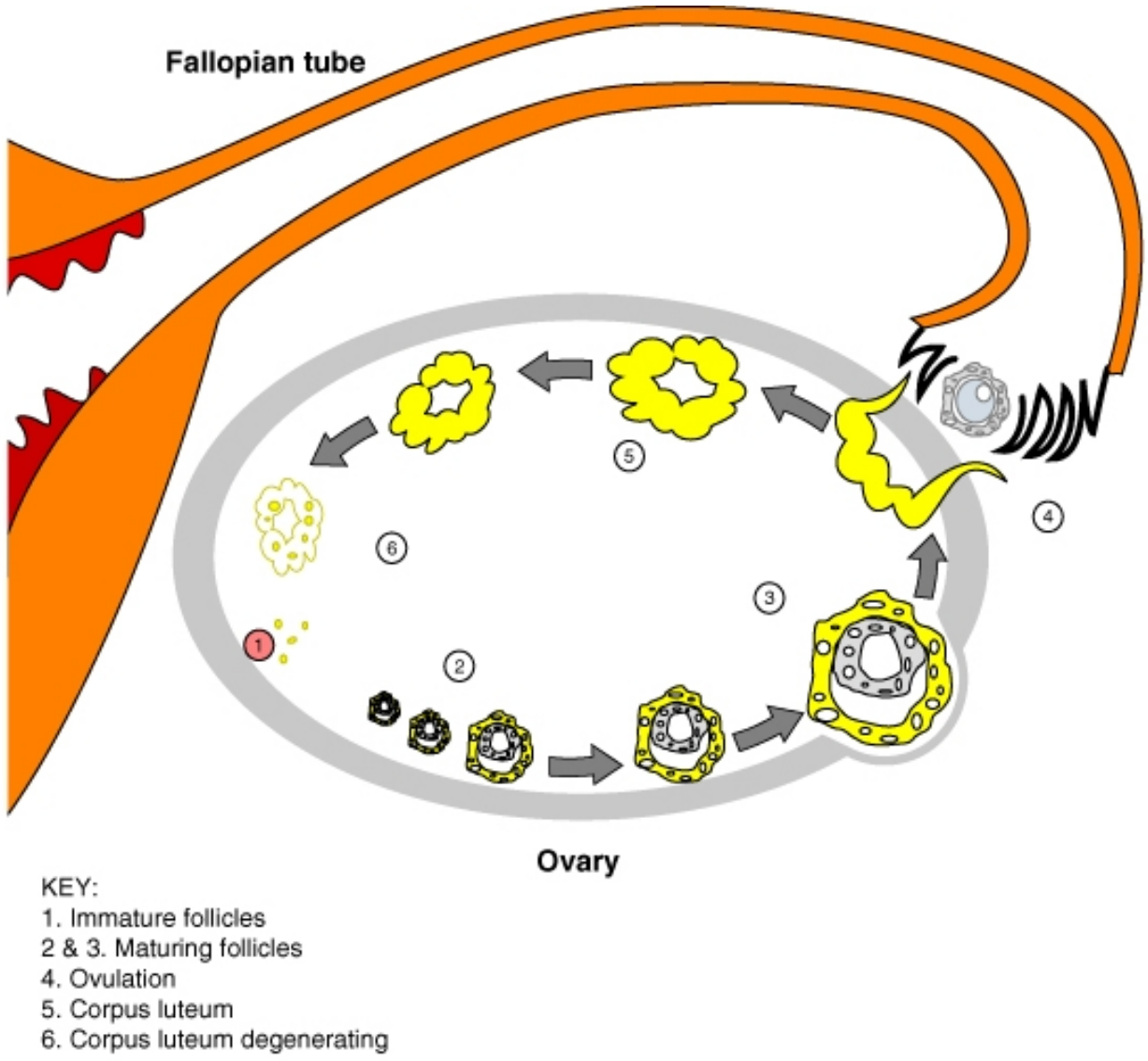


Figure 25.8: This diagram also shows the events of the menstrual cycle that occur in the ovary. After a secondary oocyte bursts from the ovary, it usually is swept into a Fallopian tube. The waving, fringelike ends of the tube help capture the egg.

Menstrual Cycle and Menstruation

Ovulation is part of the **menstrual cycle**, which occurs each month in a sexually mature female. Another part of the cycle is menstruation. **Menstruation** is the process in which blood and other tissues are shed from the uterus and leave the body through the vagina. It is also called a menstrual period, or menses. The menstrual cycle is sometimes divided into two cycles, called the ovarian cycle and the uterine cycle. The ovarian cycle includes the events that occur in the ovary. The uterine cycle refer to the events that occur in the uterus. The two cycles are closely related, so here they are described together and referred to jointly as the menstrual cycle.

Phases of the Menstrual Cycle

The phases of the menstrual cycle are summarized in **Table** 25.5. The cycle begins with the menstrual phase, which typically lasts from one to four days. This is when menstruation occurs. During the menstrual phase, arteries that supply the endometrium of the uterus constrict and break. Gradually, blood and endometrial tissues detach from the inside of the uterus and pass from the uterus to the vagina and then out of the body. If there is an immature egg in the uterus, it passes out of the body with the menstrual flow.

The menstrual cycle (as shown in **Table** 25.5) includes an ovarian and a uterine cycle. Events in the ovarian cycle include maturation of a follicle, release of an egg, and formation of the corpus luteum. Events in the uterine cycle include menstruation, development of the endometrium, and thickening of the endometrium in preparation for an egg.

Table 25.5: **The Phases of the Menstrual Cycle**

Name of Phase	Days	Events
Menstrual Phase	1–4	Menstruation occurs
Follicular Phase	5–13	Follicle matures Endometrium develops
Ovulation	14	Ovary releases egg
Luteal Phase	15–28	Follicle becomes corpus luteum Endometrium prepares for egg

The next phase of the cycle is called the **follicular phase**. After menstruation, the endometrium in the uterus begins to build up again. At the same time, several follicles start maturing in the ovary. Only one of these maturing follicles will complete maturation. The rest will eventually deteriorate and disappear. By the middle of the menstrual cycle, around day 14, the remaining mature follicle releases its oocyte from the ovary in the process of ovulation.

Following ovulation, the **luteal phase** begins. During the luteal phase, the endometrium of the uterus continues to prepare for a fertilized egg. For example, it becomes thicker and develops more blood vessels. At the same time, the mature follicle that just released its egg develops into a structure called a corpus luteum (**Figure** 25.8).

If the egg is fertilized and implants, or embeds itself, in the endometrium of the uterus, the endometrium will be maintained and help nourish it. If the egg is not fertilized, the endometrium will break down, leading to menstruation. This begins a new cycle.

The events of the menstrual cycle always occur in the same sequence, but their timing may vary considerably. There is a great deal of normal variation in the length of the overall cycle and of the individual phases. Variation may occur from one female to another and also from one cycle to the next for a given female.

Some females have symptoms—such as bloating, abdominal cramps, and mood swings—for several days before or during menstruation each month. If the symptoms are severe enough to interfere with daily life, the condition is called premenstrual syndrome, or PMS. Symptoms of PMS often can be helped with medications or lifestyle changes.

Role of Hormones

The same hormones that control female puberty and oogenesis also control the menstrual cycle: estrogen, LH, and FSH. Estrogen controls the secretion of the two pituitary hormones by acting on the hypothalamus, which controls the pituitary gland. This is shown in **Figure** 25.9. When the estrogen level rises in the blood, it stimulates the pituitary (via the hypothalamus) to secrete more or less LH and FSH.

In negative feedback, rising levels of hormones feedback to the hypothalamus and pituitary gland to decrease production of the hormones. In positive feedback, rising levels of hormones feedback to increase hormone production. During most of the menstrual cycle, estrogen and progesterone provide negative feedback to the hypothalamus and pituitary gland. This keeps their levels more or less constant. During days 12–14, however, estrogen provides positive feedback to the hypothalamus and pituitary gland. This causes a rapid rise in the production of estrogen by the ovary and leads to ovulation.

Another hormone involved in the menstrual cycle is progesterone. The word ”progesterone” literally means “pro-gestational hormone.” **Progesterone** is a hormone that promotes gestation, or the carrying of a fetus. The function of progesterone in the menstrual cycle is to maintain the endometrium of the uterus.

Change in the levels of these four hormones (estrogen, LH, FSH, and progesterone) occur during the menstrual cycle (**Figure** 25.10). After menstruation occurs, estrogen secreted by the ovaries increases. This causes the endometrium of the uterus to thicken. FSH from the pituitary stimulates follicles in the ovary to mature. The maturing follicles produce estrogen, and the level of estrogen in the blood rises. When estrogen reaches a high level in the blood,

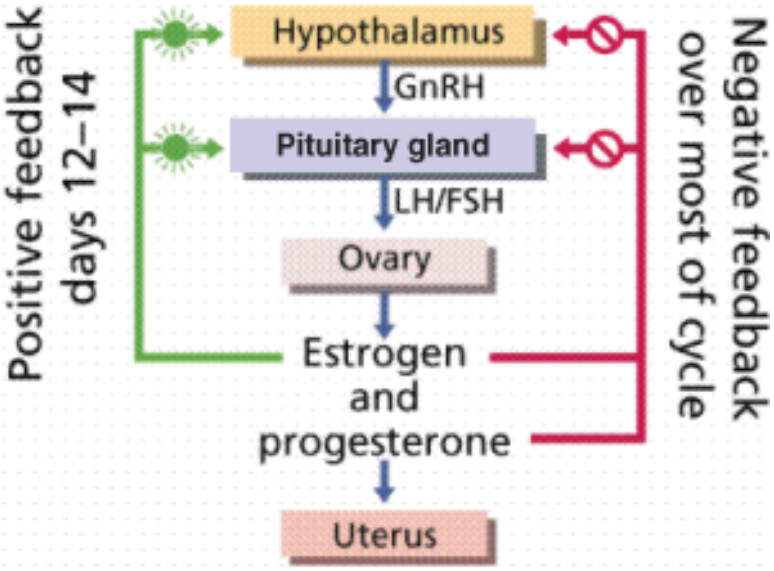


Figure 25.9: This diagram shows how hormones control the menstrual cycle with negative and positive feedback.

it stimulates the pituitary gland to release a surge of LH. The spike in LH stimulates the one remaining mature follicle to burst open and release its oocyte.

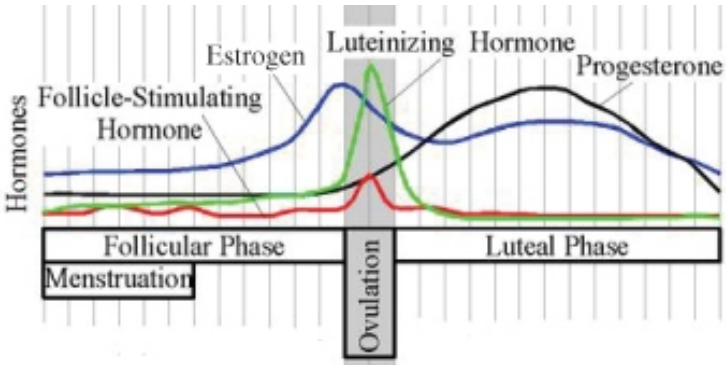


Figure 25.10: This graph shows how hormone levels change during the menstrual cycle.

During the first half of the cycle, negative feedback keeps levels of FSH, LH, estrogen, and progesterone relatively stable. During ovulation, positive feedback causes a burst of FSH, LH, and estrogen. During the second half of the cycle, progesterone rises as the corpus luteum in the ovary matures and produces this hormone. Negative feedback helps keep levels of the other three hormones fairly constant

After the oocyte is released, LH stimulates the mature follicle to develop into a corpus luteum. The corpus luteum then starts secreting progesterone, which maintains the endometrium of the uterus. What happens next depends on whether the egg has been fertilized.

- If the egg has been fertilized, it will soon start producing a hormone that helps maintain the corpus luteum. As a result, the corpus luteum will continue producing progesterone and maintain the endometrium.
- If the egg has not been fertilized, the corpus luteum will disintegrate and stop producing progesterone. Without progesterone, the endometrium will break down, detach from the uterus, and pass out of the body during menstruation.

Menopause

For most women in the U.S., the menstrual cycle continues into their forties. Then it gradually becomes more and more irregular until it finally stops altogether, generally by their early fifties. **Menopause** occurs when a woman has gone through 12 consecutive months without a menstrual period. She can no longer reproduce because her ovaries no longer produce eggs.

The cause of menopause is a natural decline in estrogen secretion by the ovaries as a woman ages. It may take from several months to a few years for her body to adjust to the drop in estrogen. During this time, she may experience hot flashes, mood swings, and other symptoms.

Lesson Summary

- The female reproductive system forms before birth but does not become capable of reproduction until it matures during puberty.
- The female reproductive system includes organs and other structures that produce and release eggs, secrete female sex hormones, and enable the development and birth of a fetus.
- Immature eggs form in the ovaries before birth. Each month, starting in puberty, one egg matures and is released from the ovary.
- The menstrual cycle includes events that take place in the ovary, such as ovulation, and changes in the uterus, including menstruation. The menstrual cycle controlled by the hormones estrogen, progesterone, LH, and FSH.

Review Questions

1. List three functions of the female reproductive system.
2. State two ways that puberty differs in girls and boys.
3. Describe the uterus and its functions in reproduction.
4. What is ovulation and when does it occur?
5. Tara is 13 and worried that she may not be developing normally. She began developing breasts about six months ago but still has not had her first menstrual period. Should

she be concerned? Explain your answer.
6. Explain how blockage of both Fallopian tubes would affect a woman's ability to reproduce naturally.
7. Create a timeline showing the steps in which an oogonium develops into a mature egg.
8. Explain the roles of estrogen, LH, and FSH in the menstrual cycle.

Further Reading / Supplemental Links

- Stanley, Deborah, Sexual Health Information for Teens. Omnigraphics, 2003.
- Walker, Pam and Wood, Elaine, Understanding the Human Body: The Reproductive System. Lucent Books, 2002.
- http://en.wikibooks.org/wiki/Human_Physiology/The_female_reproductive_system
- http://www.kidshealth.org/parent/general/body_basics/female_reproductive_system.html
- http://www.kidshealth.org/teen/sexual_health/changing_body/female_repro.html
- http://www.medicalook.com/human_anatomy/systems/Female_reproductive_system.html
- http://www.merck.com/mmhe/sec22/ch241/ch241a.html
- http://en.wikipedia.org

Vocabulary

adolescent growth spurt Rapid growth in height seen during puberty.

corpus luteum Formed in the ovary from the ruptured follicle after ovulation; if the egg is not fertilized by a sperm, the corpus luteum degenerates and virtually disappears from the ovary; produces progesterone.

egg (ova) Female gamete, or sex cell, which is necessary for reproduction; haploid.

estrogen Major female sex hormone.

Fallopian tube Tube which accepts oocyte after ovulation; site of fertilization; attached to uterus.

female reproductive system System with several major functions: producing eggs, secreting female sex hormones, receiving sperm during sexual intercourse, supporting the development of a fetus, delivering a baby during birth, and breastfeeding a baby after birth.

follicle Structure in which each egg is located; consists of the egg surrounded by special cells that protect the egg until puberty and then help the egg mature.

follicle-stimulating hormone (FSH) Hormone that stimulates the ovary to produce estrogen.

luteinizing hormone (LH) The main pituitary hormone responsible for puberty in females; stimulates the ovary to produce estrogen.

menarche The beginning of menstruation, or monthly periods.

menopause When a woman has gone through 12 consecutive months without a menstrual period; she can no longer reproduce because her ovaries no longer produce eggs.

menstruation The process in which blood and other tissues are shed from the uterus and leave the body through the vagina; also called a menstrual period, or menses.

oogenesis The process of producing eggs in the ovary.

ovary Small, oval-shaped organs that lie on either side of the uterus; the egg-producing organs of the female reproductive system; contain hundreds of thousands of immature eggs.

ovulation The release of a secondary oocyte by the ovary; occurs every 28 days, on average.

progesterone A hormone that promotes gestation, or the carrying of a fetus; also maintains the endometrium of the uterus.

uterus A muscular organ where a fetus grows and develops until birth; has a thick lining of tissues known as the endometrium; the lower, narrower end of the uterus is called the cervix.

vulva The external female reproductive structures; includes the labia and mons pubis.

Points to Consider

- If an egg is fertilized by a sperm and implants in the uterus, the endometrium helps support and nourish it. However, the new organism soon needs more nutrients than the endometrium can provide. It needs to obtain nutrients from the mother's blood. How does this happen?
- What structures are involved with pregnancy? When do they develop?

25.3 Lesson 25.3: Fertilization, Gestation, and Development

Lesson Objectives

- Explain how fertilization, cleavage, and implantation lead to the formation of an embryo.
- Describe how the embryo forms specialized cells and organs through the processes of gastrulation, differentiation, and organogenesis.
- Identify major events in the growth and development of the fetus.
- Explain how the placenta provides the fetus with oxygen and nutrients and eliminates fetal wastes.
- Describe how an expectant mother can help her fetus grow and develop normally, and summarize the events of childbirth.
- Sequence milestones in growth and development from infancy through adolescence.
- Describe the life stages of early and middle adulthood and old age, and explain why aging occurs.

Introduction

Sexual reproduction begins when an egg is fertilized by a sperm and implants in the uterus. Following these events, the remainder of growth and development before birth is divided into two main stages. The first stage is the embryonic stage, which lasts about two months. This is followed by the fetal stage, which lasts for another seven months until birth.

Fertilization, Cleavage, and Implantation

A day or two after an ovary releases an egg, the egg may unite with a sperm. However, before it becomes an embryo, it must go through other processes. These processes include cleavage and implantation.

Fertilization

Fertilization is the union of a sperm and an egg. Recall that a sperm is a male gamete and an egg is a female gamete. Each gamete is a haploid cell. When the two cells unite during fertilization, they form a diploid cell, called a **zygote.**

Fertilization generally occurs in a Fallopian tube. After sperm are deposited in the vagina during sexual intercourse, they "swim" through the cervix and uterus and into a Fallopian tube. Although millions of sperm are deposited, only a few hundred are likely to reach the

egg. A sperm about to penetrate an egg is shown in **Figure** 25.11. When a sperm finally breaks through the egg's cell membrane, it sets off a reaction that prevents other sperm from entering. The entry of the sperm also triggers the egg to complete the second meiotic division that began before ovulation.

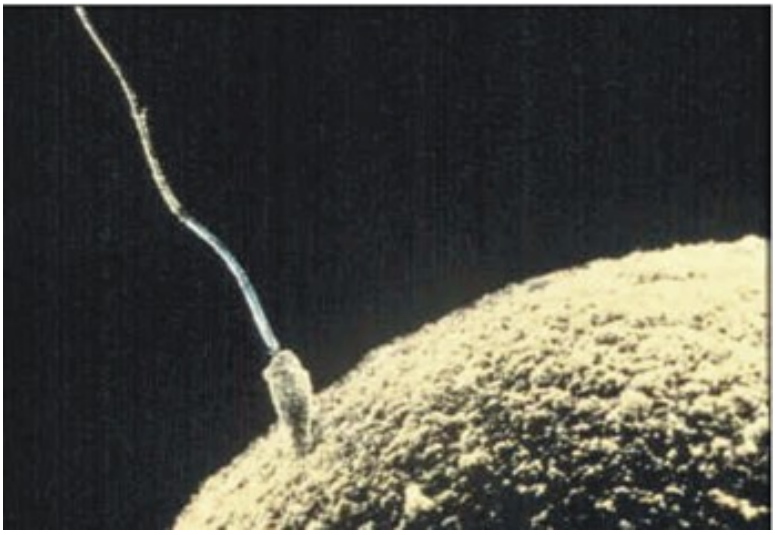


Figure 25.11: Human sperm and egg.

After the sperm penetrates the egg, its tail falls off, and its nucleus fuses with the nucleus of the egg. The resulting zygote contains all the chromosomes needed for a new individual. Half the chromosomes are from the egg, and half are from the sperm.

Cleavage

The zygote spends the next few days traveling down the Fallopian tube. As it travels, it divides by mitosis several times to form a ball of cells called a **morula**. The cell divisions, which are called **cleavage**, increase the number of cells but not their overall size. More cell divisions occur, and soon a fluid-filled cavity forms inside the ball of cells. At this stage, the ball of cells is called a **blastocyst**. The process of blastocyst formation is shown in **Figure** 25.12.

The cells of the blastocyst form an inner and an outer cell layer. This is apparent in **Figure** 25.13. The inner layer of cells is called the embryoblast. This layer of cells will soon develop into an embryo. The outer layer of cells is called the trophoblast. This layer will develop into other structures, including the placenta, which you will read more about below.

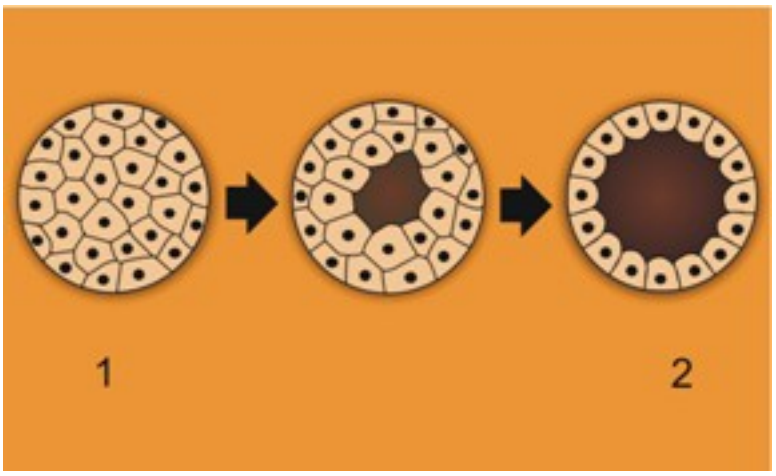


Figure 25.12: The morula (1) continues to undergo cell divisions. As it does, cells start to migrate into separate layers, and a cavity starts to develop inside the ball of cells. When cells have migrated into distinct layers, the organism is called a blastocyst (2).

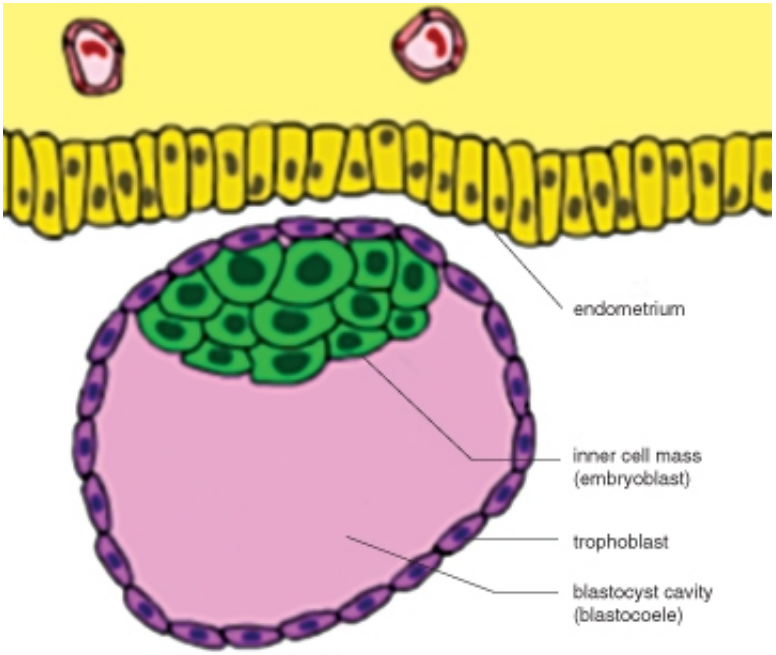


Figure 25.13: The blastocyst consists of an outer layer of cells called the trophoblast, a fluid-filled cavity, and an inner cell mass called the embryoblast.

Implantation

The blastocyst continues the trip down the Fallopian tube and reaches the uterus about four or five days after fertilization. When the outer cells of the blastocyst contact cells lining the uterus, the blastocyst embeds in the lining. The process of embedding is called **implantation**. It generally occurs about a week after fertilization. Once implantation occurs, the blastocyst is called an embryo.

Growth and Development of the Embryo

An **embryo** is a developing human being from the time of implantation through the first eight weeks after fertilization. During this time, the embryo grows in size and undergoes three processes: gastrulation, differentiation, and organogenesis.

Gastrulation

Gastrulation is the development of different layers of cells in the embryo. It generally occurs during the second week after fertilization. During gastrulation, cells of the embryo migrate to form three distinct cell layers: the ectoderm, mesoderm, and endoderm. These layers are shown in **Figure** 25.14. Each layer will eventually develop into certain types of tissues and cells in the body.

- **Ectoderm**—Forms tissues that cover the outer body; develops into cells such as nerves, skin, hair, and nails.
- **Mesoderm**—Forms tissues that provide movement and support; develops into cells such as muscles, bones, teeth, and blood.
- **Endoderm**—Forms tissues involved in digestion and breathing; develops into cells such as lungs, liver, pancreas, and gall bladder.

Differentiation and Organogenesis

During the third week after fertilization, the embryo begins to undergo cellular differentiation. **Differentiation** is the process by which unspecialized cells become specialized into one of the many different types of cells that make up the body. During differentiation, certain genes are turned on, or activated, while other genes are switched off, or inactivated. As a result of this process, cells develop specific structures and abilities that suit them for their specialized roles in the body. Several examples of specialized cells are shown in **Figure** 25.14, along with the cell layers from which they develop.

Differentiation of cells leads to the development of specific organs within the three cell layers. This is called **organogenesis**. All the major organs begin to form during the remaining

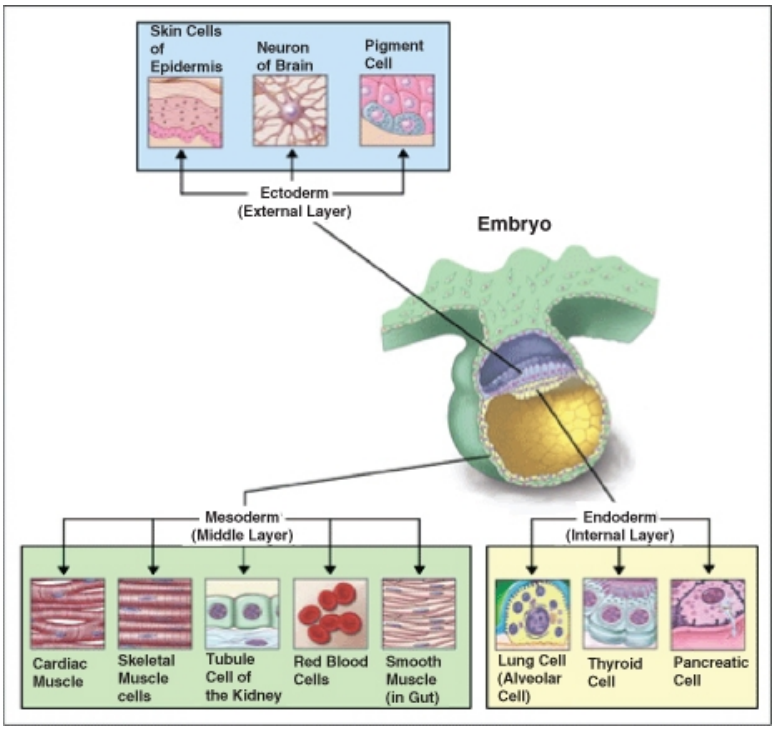


Figure 25.14: The three cell layers of the embryo develop into different types of cells. For example, the ectoderm develops into skin cells, the mesoderm into muscle cells, and the endoderm into lung cells.

weeks of embryonic development. A few of the developments that occur in weeks 4 through 8 are listed below.

Embryonic Development During Weeks 4-8

Pictured above is a 4-week-old embryo.

At Week 4

- Heart begins to beat.
- Arm buds appear.
- Liver, pancreas, and gall bladder start to form.
- Spleen appears.

At Week 5

- Eyes start to form.
- Leg buds appear.
- Hands appear as paddles.
- Blood begins to circulate.
- Facial features start to develop.

At Week 6

- Lungs start to form.
- Fingers and toes form.

At Week 7

- Hair follicles start to form.

- Elbows and toes are visible.

At Week 8

- Facial features look more human.
- External ear begins to take shape.

As the embryo develops, it also grows in size. By the eighth week of development, the embryo is about 30 millimeters long. It may also have begun to move.

Growth and Development of the Fetus

From week 8 until birth, the developing individual is referred to as a **fetus**. In humans, birth typically occurs 38 weeks after fertilization, so the fetal period lasts about 30 weeks. During this time, the organs that formed during the embryonic period go through further development. The fetus also grows in overall body size. For a detailed animation of the growth and development of the fetus see http://www.youtube.com/watch?v=aR-Qa_LD2m4&feature=related.

Weeks 8 to 15

During the fetus's early weeks, reproductive organs develop along either male or female lines. The liver starts producing red blood cells, and tooth buds appear. The fetus becomes more human in appearance, with well-formed facial features. The eyelids form but remain closed until later in fetal development. The muscles and bones develop, and the fetus is very active. It can make a fist and move its arms and legs. It also hiccups, stretches, and yawns. The first measurable brain activity occurs around the 12th week. By the end of the 15th week, the fetus is about 15 centimeters long.

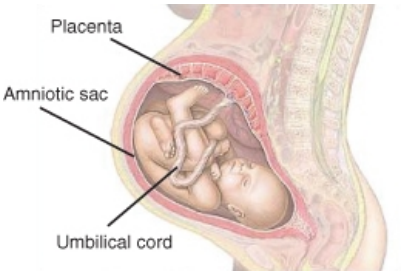
Weeks 16 to 26

A fetus at 18-weeks after fertilization is shown in **Figure ??**. At this stage, the brain is developing rapidly, and it starts to take control of some body functions. The alveoli (air sacs) in the lungs also develop, making gas exchange possible, although the lungs are still immature. Most of the internal components of the eyes and ears form and develop at this time. There is more muscle development, as well, and the fetus is more active than ever. The mother usually starts to feel fetal movement during this stage.

Fine hair called lanugo grows and covers the fetus's body by the end of this stage. Eyebrows, eyelashes, and nails also appear, and the eyelids begin to open and close. By the end of week 26, the fetus is about 38 centimeters long and weighs about 1.2 kilograms.

Weeks 27 to 38

During the final weeks of growth and development, the amount of body fat rapidly increases. Bones develop fully, although they are still soft and pliable. Most of the lanugo disappears, and head hair becomes coarser and thicker. Fingernails grow beyond the end of the fingertips. In the brain, connections form that allow the input of sensations. Starting around week 30, the brain is continuously active. By the 38th week, the fetus is fully developed and ready to be born. A 38-week fetus normally ranges from 36 to 51 centimeters in length and weighs between 2.7 and 4.6 kilograms. A 38-week-old fetus is shown in **Figure ??**.



Sometimes fetuses are born earlier than 38 weeks. After 35 weeks, the fetus is considered "full-term," which means that it is developed enough for life outside the mother. Fetuses

born before 35 weeks are likely to have health problems due to their immaturity, although many are able to survive with medical help. The less time a fetus spends developing in the uterus before it is born, the less likely it is to survive after birth. Fetuses born before 25 weeks rarely survive.

Placenta and Related Structures

The **placenta** is a temporary organ in which nutrients and wastes are exchanged between the mother and the embryo or fetus. The placenta begins to form in the second week after fertilization. It continues to develop and grow to meet the needs of the growing fetus. A fully developed placenta, like the one in **Figure ??**, is made up of a large mass of blood vessels from both the mother and fetus. The maternal and fetal vessels are close together but separated by empty space. This allows the mother's and fetus's blood to exchange substances without actually mixing.

How the Placenta Works

Blood from the mother enters the maternal blood vessels of the placenta under pressure, forcing the blood into the empty spaces. When the mother's blood contacts the fetal blood vessels, gases are exchanged. Oxygen from the mother's blood is exchanged with carbon dioxide from the fetus's blood. A release of pressure brings the mother's blood back from the placenta and into her veins.

The fetus is connected to the placenta through the **umbilical cord**, a tube that contains two arteries and a vein. Blood from the fetus enters the placenta through the umbilical arteries, exchanges gases with the mother's blood, and travels back to the fetus through the umbilical vein.

In addition to gas exchange, the placenta transfers nutrients, hormones, and other needed substances from the mother's blood to the fetus's blood. The placenta also filters many harmful substances out of the mother's blood so they are not transferred to the fetus. In addition, the placenta secretes hormones that maintain the corpus luteum in the mother's ovary. Recall that the corpus luteum secretes progesterone, which is needed to keep the endometrium of the uterus from breaking down.

Amniotic Sac and Fluid

Attached to the placenta is the **amniotic sac**, which surrounds and protects the embryo or fetus. It begins to form in the second week after fertilization. It soon fills with water and dissolved substances to form **amniotic fluid**. The fluid allows the fetus to move freely until the fetus grows to fill most of the available space. The fluid also cushions the fetus and helps protect it from injury.

Pregnancy and Childbirth

Pregnancy is the carrying of one or more offspring from fertilization until birth. It is the development of a fetus from the expectant mother's point of view. A woman is likely to first suspect she is pregnant when she misses a menstrual period. As you just read, hormones secreted by the placenta maintain the endometrium of the uterus. This prevents menstruation from occurring once pregnancy begins.

The pregnant mother plays a critical role throughout the embryonic and fetal periods. She must provide all the nutrients and other substances needed for normal growth and development. Therefore, it is important for the expectant mother to take good care of her health during pregnancy for the sake of her baby as well as herself. Most importantly, the mother needs to avoid toxic substances and take in adequate nutrients.

Avoiding Toxins

Unfortunately the placenta cannot protect the developing embryo or fetus from all harmful substances in the mother's blood. Some harmful substances can cross the placenta from the mother's blood and damage the embryo or fetus, including:

- Alcohol
- Chemicals in tobacco smoke
- Aspirin
- Thalidomide (a prescription drug)
- Heroin
- Cocaine

These and other substances can cause birth defects. For example, if a pregnant woman drinks alcohol, it can cause variety of birth defects that are collectively called fetal alcohol syndrome. A baby with fetal alcohol syndrome is shown in **Figure** 25.15. The defects include facial abnormalities, stunted growth, and mental retardation.

Alcohol and some other toxins can damage the developing brain at any time before birth because the brain continues to develop and grow rapidly throughout pregnancy. However, in general, birth defects are likely to be more severe when exposure to toxins occurs during the embryonic period. This is because the embryo is undergoing organogenesis. Any disruption of normal development during this early period is likely to have a greater impact on the organism than later in pregnancy, when the organs are already formed. Although exposure to toxins at later stages of development may do less damage, an expectant mother should try to avoid toxins throughout her pregnancy.

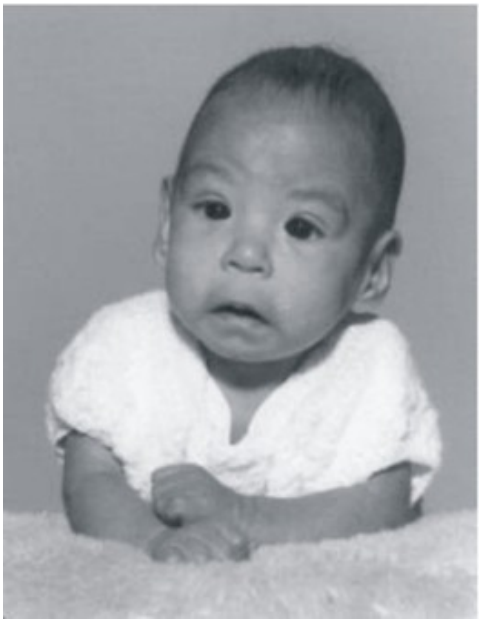


Figure 25.15: Baby with fetal alcohol syndrome.

Taking in Nutrients

The fetus depends completely on the mother for its nutrient needs. As a result, most nutrients are needed in greater amounts by a pregnant woman than a woman who is not pregnant. Some nutrients are especially important for embryonic or fetal development.

- Folic acid (vitamin B_9) is needed for normal development of the spinal cord. Inadequate folic acid intake can lead to spina bifida, a serious birth defect.
- Calcium is needed for normal development of bones and teeth.
- Iron is needed for the proper formation of red blood cells.
- Omega-3 fatty acids are important for normal development of nerve cells.

If an expectant mother eats a balance of foods from the different food groups, this diet will help ensure adequate nutrients for the fetus. Because needs for some nutrients are so high, nutrient supplements are usually recommended during pregnancy. Supplements formulated for pregnant women help supply adequate amounts of folic acid and other nutrients needed for normal growth and development of the fetus.

Childbirth

Near the time of birth, the amniotic sac breaks in a gush of fluid. Within 24 hours of the amniotic sac breaking, labor usually begins. **Labor** involves contractions of the muscular

walls of the uterus. The contractions are stimulated by the release of the pituitary hormone oxytocin. The contractions cause the cervix to widen and the passage through the cervix to dilate, or open. The contractions become closer and stronger, and the cervix gradually becomes more dilated. This may take hours or even days. When the cervix is dilated to about 10 centimeters, the baby begins to move through cervix and into the vagina.

At this point, the mother begins pushing to aid in the birth of the baby. This part of labor is generally shorter. The fetus usually emerges head first. Within seconds of birth, the umbilical cord is cut. Without this connection to the placenta, the baby cannot exchange carbon dioxide, which quickly builds up in the baby's blood. This stimulates the brain to trigger breathing and the newborn takes its first breath. Generally within half an hour or less of the birth of the baby, contractions of the uterus force the placenta and any remaining amniotic tissues from the mother's body.

By birth, a fetus has a large head relative to its body size, because the brain is more developed than any other organ. Some areas of the skull have not yet been converted to hard bone, allowing the fetus's head to change shape somewhat to fit through the cervix during birth. The head returns to its normal shape shortly after birth.

Infancy, Childhood, and Adolescence

For the first year after birth, a baby is called an infant. Early childhood begins at age two, when a child may be referred to as a toddler. Childhood continues until adolescence, which generally coincides with the teen years. Adolescence is the period of transition into adulthood.

Infancy

Infancy is defined as the first year of life after birth. For the first month after birth, an infant is called a newborn. A newborn has a distinctive appearance. The head is very large, and the arms and legs are relatively short. The shoulders and hips are narrow, and the abdomen protrudes slightly. Many newborns still have lanugo on some areas of their body, but this usually disappears within a few weeks after birth. Head hair can vary from almost no hair to a full head of hair. The stub of the umbilical cord remains for a few weeks, until it dries up and falls off, forming the navel.

Infants are born with certain abilities already developed. For example, they have a well developed sense of smell. They can also communicate their needs by crying when they are hungry, uncomfortable, bored, or lonely. During their first year, they develop many other abilities:

- By 6 weeks after birth, babies typically start smiling (**Figure** 25.16) and making vocal sounds.

- By 6 months, they spend a lot of time babbling. They have also learned to sit and are starting to crawl.
- By 12 months, they are saying their first words. They can stand with help and may have started to walk.

Figure 25.16: Six-week-old baby's first smile.

Infancy is the period of most rapid growth after birth. Growth during infancy is even faster than growth during puberty. By the end of the first year, the average baby is twice the length it was at birth and three times its birth weight. Infancy is also the period when most of the deciduous, or "baby," teeth erupt. The front teeth erupt first, usually starting around six months after birth. There are 20 deciduous teeth altogether, and they continue to erupt until about three years of age.

Newborns need about 18 hours of sleep each day. They usually sleep in long naps throughout the day and night. As infants get older, they need less sleep. They also start to sleep through the night and just take short naps during the day. When newborns aren't sleeping, they are usually feeding. Breastfeeding is the recommended method of feeding infants. Breast milk is generally supplemented by other foods by the end of the first year.

Childhood

A **toddler** is a young child who is learning to walk, or "toddle." This is the second stage of development after infancy. It generally refers to children between the ages of 1 and 3 years. During this stage, children not only learn to walk steadily but also develop other motor skills. By the end of the third year, most children can run, walk up steps, and climb onto chairs. They can feed and dress themselves with help. They can also manipulate small objects and hold a crayon and scribble with it. They have learned dozens of words and are speaking in simple sentences. Most children are also toilet trained by the end of the third year.

Growth is still relatively rapid during the toddler years but slowing down. By the time children are five years old, their height is increasing by only about 5 percent per year,

compared with 100 percent per year in the first year of life. By age five, children are able to carry on conversations, recognize letters and words, and tie their shoe laces. Five-year olds can use a pencil to trace letters and other shapes (**Figure** 25.17). They also may be learning to ride a bicycle, swim, swing a bat, or kick a ball.

Figure 25.17: A five-year old using a pencil to trace shapes.

By age six, most children begin losing their deciduous teeth, and their permanent teeth erupt to replace them. This continues until about age 12. Other important changes of older childhood include the transition from home to school. At school, children not only acquire academic skills such as reading, but also interact more with their peers. They form friendships and are likely to have "best" friends. Older children continue to grow slowly until they start the adolescent growth spurt during puberty.

Adolescence

Adolescence is the period of life between the beginning of puberty and adulthood. You learned about the physical changes of puberty earlier in this chapter. Adolescence is also a time of significant mental, emotional, and social changes. For example, during adolescence, teens develop more advanced mental abilities, including the ability to think abstractly. They also try to establish an identity, or sense of self. In the process, they may try to become more independent from their parents. They may also challenge authority and push limits.

Emotionally, adolescence may be a time of upheaval. Shifting hormone levels may cause mood swings at a time when many adolescents are still learning how to manage their emotions. One of the most important social changes of adolescence is the increased importance of peers. Teens spend much more time with their friends and other peers than younger children do, and they are generally greatly influenced by them. Young people may also start to develop intimate relationships during adolescence.

Adulthood and Old Age

The development of intimacy is considered to be a major goal of the stage of life referred to as young adulthood. Other stages of adulthood include middle adulthood and old age. Each stage is associated with particular goals and health concerns.

When Does Adulthood Start?

The age at which adulthood starts may vary from about age 17 to 21 years, depending on how adulthood is defined. A person may be physically mature by age 17 but not considered legally mature until an older age. For example, in the U.S., individuals cannot assume adult responsibilities, such as voting and joining the armed forces, until they are 18 years old. They cannot exercise certain adult rights, such as buying and using alcohol, until they are 21.

Early and Middle Adulthood

Early adulthood may be defined as the stage of life from the start of adulthood through age 34 years. During early adulthood, people generally learn how to form intimate relationships, both in friendship and love. Many people become engaged or marry during this time. Young adults may also be involved in completing their education and becoming established in a career or the workforce. Health problems in most young adults are minor. The most common causes of death are due to violence: homicides, car crashes, and suicides.

Middle adulthood may be defined as the stage of life from age 35 through 64 years. During this stage, most people raise a family (if they are going to) and strive to attain career goals. They are more likely to become involved in their community.

During middle adulthood, people start showing physical signs of aging, such as wrinkled skin and gray hair. Vision, strength, reaction time, and overall fitness also typically decline during middle adulthood. At the same time, health problems tend to increase. Diseases such as type 2 diabetes, cardiovascular disease, and many types of cancer are often diagnosed during this stage of life, especially in people who are overweight or obese. The risk of being diagnosed with diseases such as these increases throughout middle adulthood. These diseases are also the chief causes of death of middle adults.

Old Age

Old age may be defined as the stage from age 65 until death. During this stage, most people retire from work and no longer have the major responsibility of caring for others. Physically, older adults tend to have a decline in stamina, strength, reflex time, and the senses.

Other physical changes that occur in old age include a decrease in:

- heart output
- kidney function
- lung capacity
- number of brain cells

Because the immune system also becomes less efficient with age, older adults are increasingly susceptible to serious illnesses such as cancer, cardiovascular disease, and pneumonia. Osteoporosis, or loss of bone density, is also common in older adults, particularly in females. Mental deterioration may occur, as well, especially in people with Alzheimer's disease and certain other diseases. Otherwise, intelligence tends to remain stable throughout adulthood and into old age.

Why does aging occur? Why does the body decline in function as people grow old? There are at least two reasons. One reason is that cells are programmed to divide a set number of times. After that, they can no longer divide, so they die out. Another reason is that DNA becomes increasingly damaged through time due to mutagens in the environment. Eventually, the damage accumulates to a point where cells can no longer divide. Most physical changes associated with aging may be due to a combination of both processes.

Lesson Summary

- Fertilization is the union of a sperm cell and an egg cell that forms a zygote. The zygote undergoes many cell divisions before it implants in the lining of the uterus.
- The embryonic stage begins with implantation. An embryo forms three distinct cell layers, and each layer develops into different types of cells and organs.
- The fetal stage begins about two months after fertilization and continues until birth. During this stage, the organs grow and develop and the fetus grows in size.
- The placenta allows nutrients and wastes to be exchanged between the mother and fetus. The fetus is connected to the placenta through the umbilical cord.
- A pregnant woman should avoid toxins and take in adequate nutrients for normal fetal growth and development. During childbirth, the fetus is pushed through the cervix and out of the body through the vagina.
- Growth and development are most rapid during infancy and slower throughout the rest of childhood until adolescence. Adolescence involves mental, emotional, and social changes in addition to the physical changes of puberty.

- During early adulthood, people form intimate relationships and start careers. Serious health problems start showing up in middle adulthood and old age. Aging occurs as cells lose their ability to divide.

Review Questions

1. Describe what happens during fertilization.
2. How does gastrulation change an embryo?
3. Identify three events that occur as a fetus grows and develops.
4. Explain the role of the placenta in fetal development.
5. Why is an embryo generally more susceptible than a fetus to damage by toxins in the mother's blood?
6. Why is the umbilical cord cut before a newborn has started to breathe on its own?
7. Create a timeline of growth and development from infancy through adolescence.
8. Explain why aging occurs.

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Vocabulary

adolescence The period of life between the beginning of puberty and adulthood.

amniotic fluid Fluid that allows the fetus to move freely within the amniotic sac; also cushions the fetus and helps protect it from injury.

blastocyst The ball of cells that contains a fluid filled cavity and distinct layers; forms from the morula.

cleavage The initial cell divisions which increase the number of cells but not their overall size.

differentiation The process by which unspecialized cells become specialized into one of the many different types of cells that make up the body.

ectoderm Cell layer of the embryo that forms tissues that cover the outer body; develops into cells such as nerves, skin, hair, and nails.

embryo A developing human being from the time of implantation through the first eight weeks after fertilization.

embryoblast Inner layer of cells of the blastocyst; develops into an embryo.

endoderm Cell layer of the embryo that forms tissues involved in digestion and breathing; develops into cells such as lungs, liver, pancreas, and gall bladder.

fertilization The union of a sperm and an egg. When the two cells unite during fertilization, they form a diploid cell, called a zygote.

fetus The developing individual from week 8 until birth.

gastrulation The development of different layers of cells in the embryo; generally occurs during the second week after fertilization.

implantation The embedding of the blastocyst in the lining of the uterus; occurs about a week after fertilization. Once implantation occurs, the blastocyst is called an embryo.

infancy The first year of life after birth.

mesoderm Cell layer of the embryo that forms tissues that provide movement and support; develops into cells such as muscles, bones, teeth, and blood.

morula Initial ball of cells formed the first few days after fertilization; formed within a fallopian tube.

organogenesis The development of specific organs within the three cell layers.

placenta A temporary organ in which nutrients and wastes are exchanged between the mother and the embryo or fetus.

pregnancy The carrying of one or more offspring from fertilization until birth.

trophoblast Outer layer of cells within the blastocyst; will develop into structures which includes the placenta.

Points to Consider

- Many diseases become more common as people age, but some diseases are more common in adolescents and young adults, including sexually transmitted diseases (STDs). What are examples of STDs?
- How common are STDs in teens and young adults?
- Why are STDs more common during these two stages of life?

25.4 Lesson 25.4: Sexually Transmitted Diseases

Lesson Objectives

- Explain how STDs are transmitted and how they can be prevented.
- Identify and describe three common bacterial STDs.
- Identify and describe three common viral STDs.

Introduction

A **sexually transmitted disease (STD)** is an illness caused by a pathogen that is transmitted from one person to another mainly through sexual contact. Worldwide, as many as one million people a day become infected with STDs. The majority of these infections occur in people under the age of 25.

Sexually Transmitted Diseases

Common STDs include chlamydia, gonorrhea, syphilis, human immunodeficiency virus (HIV) infection, genital herpes, hepatitis B, and genital warts. To be considered an STD, a disease must have only a small chance of spreading naturally in ways other than sexual contact. Many diseases that can spread through sexual contact spread more commonly by other means. These diseases are not considered STDs.

Pathogens that Cause STDs

STDs may be caused by several different types of pathogens, including protozoa, insects, bacteria, and viruses.

- The protozoa *Trichomonas vaginalis* causes an STD called trichomoniasis. This is an infection of the vagina in females and the urethra in males.
- Pubic lice, like the one in **Figure** 25.18, are insect parasites that can be transmitted sexually. They suck the blood of their host and irritate the skin in the pubic area.

Figure 25.18: A magnified pubic louse ().

Although these STDs are common, the majority of STDs are caused by bacteria or viruses. Several bacterial and viral STDs are described below. It is important to note that most bacterial STDs can be cured with antibiotics, whereas viral STDs do not have cures, although some can be prevented with vaccines.

How STDs Spread

Most of the pathogens that cause STDs enter the body through mucous membranes of the reproductive organs. All sexual behaviors that involve contact between mucous membranes put a person at risk for infection. This includes vaginal, anal, and oral sexual behaviors.

Many STDs can also be transmitted through body fluids such as blood, semen, and breast milk. For example, in the past, HIV and hepatitis B were transmitted through blood transfusions. This no longer occurs because donated blood is now screened for the pathogens. Use of shared injection or tattoo needles is another way in which blood and pathogens can be transferred from one person to another. A number of STDs can also be transmitted from a mother to her baby through her blood during childbirth or through her breast milk after birth.

STDs are much more common in young adults and teens than in older people. One reason is that young people are more likely to take risks and to think "It can't happen to me." They also may not know how STDs are spread. In addition, younger people may be more sexually active than older people.

Preventing STDs

The only completely effective way to prevent infection with STDs is to avoid sexual activity and other known risk behaviors, such as using contaminated needles. Using condoms can decrease the risk of contracting STDs during some types of sexual activity. However, using condoms is not a foolproof method. Pathogens may be present on areas of the body not

covered by condoms. Condoms can also break or be used incorrectly.

Bacterial STDs

Many STDs are caused by bacteria. Some of the most common bacterial STDs are chlamydia, gonorrhea, and syphilis.

Chlamydia

Chlamydia is an STD caused by the bacterium *Chlamydia trachomatis*. It is the most common STD in the U.S. Each year, about four million new chlamydia infections occur in Americans. As shown in **Figure** 25.19, females are much more likely to develop chlamydia than males. This figure also shows how common this STD is in teens and young adults compared with older people. This is typical of most STDs.

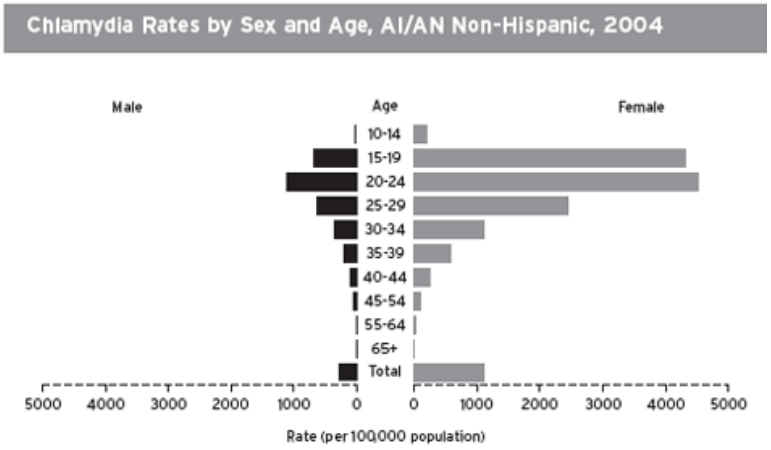

Figure 25.19: This bar graph shows the number of cases of chlamydia per 100,000 people in the United States in 2004, by age and sex. Chlamydia rates were greatest from both sexes between the ages of 15 and 34 years. The rates in females at all ages were much greater than the rates in same-aged males.

Symptoms of chlamydia may include a burning sensation during urination and a discharge from the vagina or penis. Chlamydia can be cured with antibiotics. However, in the majority of cases, there are no symptoms. As a result, many people are not aware they are infected and do not seek treatment.

It is important to detect and treat chlamydia infections even when they do not cause symptoms. Untreated chlamydia can lead to more serious problems, especially in females. Almost

half of all women with untreated chlamydia develop **pelvic inflammatory disease (PID)**, which is an infection of the uterus, Fallopian tubes, and/or ovaries. PID can lead to scarring of the reproductive organs, which may cause pain and difficulty becoming pregnant. Chlamydia causes an estimated half million cases of PID in the U.S. each year.

In addition to sexual transmission, chlamydia can be passed from a woman to her baby before or during birth. Before birth, chlamydia infection of the fetus may cause the fetus to be born too soon. During birth, a baby's eyes can become infected with the bacteria. If the eye infection is not treated, it can lead to blindness. Because chlamydia is common and often symptomless, newborns are treated routinely with eye drops to prevent chlamydia eye infections from developing.

Gonorrhea

Gonorrhea is an STD caused by the bacterium *Neisseria gonorrheae*. Gonorrhea is also a common STD. In the U.S., an estimated 700,000 people are infected with gonorrhea each year.

Symptoms of gonorrhea may include painful urination and discharge from the vagina or penis. Gonorrhea usually can be cured with antibiotics, although the bacteria have developed resistance to the most commonly used antibiotics. Gonorrhea infections may not cause symptoms, especially in females, so they often go untreated. Untreated gonorrhea can lead to PID in females. In males, it can lead to inflammation of the epididymis, prostate, and urethra.

Gonorrhea can be passed from an infected woman to her baby during childbirth. This may cause an eye infection. The infection must be treated promptly to prevent blindness.

Syphilis

Syphilis is an STD caused by the bacterium *Treponema pallidum*. In the U.S., about 70,000 new cases of syphilis occur each year. Syphilis is less common than either chlamydia or gonorrhea, but it is more serious if it is not treated. Untreated syphilis can even cause death.

Early symptoms of infection with syphilis include the development of a small sore on or near the genitals. The sore is painless and heals on its own, so it may go unnoticed. Many people do not realize they have become infected until much later, so they do not seek treatment. If diagnosed and treated early, most cases of syphilis can be cured with antibiotics. However, if syphilis goes untreated, the disease may progress through the stages shown in **Table** 25.6. Untreated syphilis can eventually cause serious damage to the heart, brain, and other organs.

Table 25.6: **Stages of Syphilis Infection**

Stage	Time After Initial Infection	Signs and Symptoms
Primary	2 days	Small sore on genitals
Secondary	1–6 months	Rash, fever, sore throat, headache
Latent	6–12 months	None
Tertiary	1–10 years	Chronic inflammation, damage to aorta and heart, narrowing of arteries, stroke, meningitis, muscle weakness

Viral STDs

STDs caused by viruses include genital herpes, hepatitis B, genital warts, and cancer of the cervix. Another common viral STD is HIV infection, which causes acquired immune deficiency syndrome, or AIDS. HIV and AIDS are described in the chapter titled *Immune System and Disease*.

Genital Herpes

Genital herpes is an STD caused by herpes simplex virus type 2 (HSV-2). In the U.S., as many as 20% of males and 25% of females may be infected with HSV-2. The virus is closely related to herpes simplex virus type 1 (HSV-1), which causes cold sores on the lips. Both viruses are transmitted by direct contact. Both also cause similar symptoms, except HSV-2 infects the genitals instead of the mouth.

Symptoms of genital herpes include painful, fluid-filled blisters on the penis, vulva, or nearby membranes (**Figure** 25.20). The initial infection soon clears up on its own. However, herpes virus particles travel to local nerves, where they evade the immune system and remain for the life of the infected person. Periodically, some of the virus particles travel back to the skin and cause new outbreaks of blisters. Outbreaks may be triggered by stress or other factors. A person with genital herpes is most likely to transmit the virus during an outbreak.

There is no known cure for genital herpes. Once a person becomes infected, there is no way to eradicate the virus from the body. However, antiviral drugs can prevent outbreaks or reduce their length and severity. The drugs also reduce the risk of transmitting the virus. A vaccine to prevent infections with HSV-2 may soon be available.

Genital herpes may cause emotional problems because it affects intimate relationships throughout a person's life. However, it is not considered to be a serious disease from the standpoint of physical health. On the other hand, herpes is very serious for newborns if they are in-

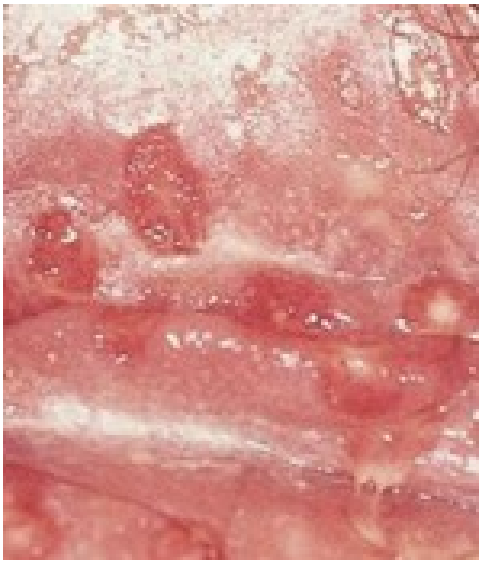

Figure 25.20: Genital herpes causes outbreaks of fluid-filled blisters, like ones shown here, on the membranes of reproductive organs.

fected with the virus during childbirth. It can lead to blindness, mental retardation, and even death.

Hepatitis B

Hepatitis B is inflammation of the liver caused by infection with the hepatitis B virus. In the U.S., there are about 200,000 new cases of hepatitis B diagnosed each year. In addition, as many as 5,000 Americans die each year from hepatitis B infections.

Early symptoms of hepatitis B include vomiting and jaundice, which is yellowing of the skin and eyes. Hepatitis B often gets better on its own after a few weeks or months and causes no long-lasting effects. However, in a small percentage of people it develops into a chronic, or long-term, disease. In some people, chronic hepatitis B causes few if any symptoms, although people infected with the virus can still spread it to others. In other people, chronic hepatitis B causes continuous inflammation of the liver. This eventually damages the liver. It also increases the risk of liver cancer, which is usually fatal.

Hepatitis B cannot be cured. Antiviral drugs can help prevent liver damage in people with chronic hepatitis B, but they cannot eradicate the virus from the body. However, vaccines have been developed to prevent hepatitis B infection.

In addition to sexual transmission, hepatitis B is commonly transmitted through contaminated needles and from mother to child during childbirth. Newborns are much more likely than older people to develop chronic hepatitis B. This is because their immune system is

immature and unable to fight off the virus.

Genital Warts and Cervical Cancer

Both genital warts and cancer of the cervix are caused by the human papillomavirus (HPV). There are more than 100 types of HPV. Some types of HPV cause common warts, which are small, rough growths on the hands, knees, or feet. These HBV viruses are transmitted by casual skin-to-skin contact. Other types of HPV cause genital warts or cervical cancer. These HPV viruses are transmitted through sexual contact. Genital HPV infections are very common. In the U.S., more than six million people become infected each year.

Many types of HPV that are transmitted sexually do not cause any noticeable symptoms. However, several types cause genital warts or cervical cancer. Cervical cancer is easily detected with a Pap test, which involves examining a sample of cervical cells for cancerous changes. If detected early, cervical cancer can be cured with surgery. Since 2006, a vaccine has been available to prevent transmission of the most common types of HPV that cause genital warts and cervical cancer. The vaccine is recommended for females from aged 11 to 26 years.

Lesson Summary

- STDs are diseases caused by pathogens that spread through sexual contact. Abstinence from sexual activity is the only completely effective way to prevent the spread of STDs.
- Bacterial STDs include chlamydia, gonorrhea, and syphilis. These diseases can be cured with antibiotics.
- Viral STDs include genital herpes, hepatitis B, genital warts, and cervical cancer. These diseases cannot be cured, but some of them can be prevented with vaccines.

Review Questions

1. Describe how STDs spread.
2. What is the only completely effective way to prevent infection from STDs?
3. Identify three common STDs that are caused by bacteria.
4. Name and describe an STD caused by a virus.
5. Why is it important to treat STDs even when they do not cause symptoms?
6. How does lack of symptoms contribute to the spread of STDs?

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Vocabulary

chlamydia A STD caused by the bacterium *Chlamydia trachomatis*; the most common STD in the U.S. Each year, about four million new chlamydia infections occur in Americans.

genital herpes An STD caused by herpes simplex virus type 2 (HSV-2). In the U.S., as many as 20% of males and 25% of females may be infected with HSV-2.

gonorrhea An STD caused by the bacterium *Neisseria gonorrheae.* In the U.S., an estimated 700,000 people are infected with gonorrhea each year.

hepatitis B An inflammation of the liver caused by infection with the hepatitis B virus.

pelvic inflammatory disease (PID) An infection of the uterus, Fallopian tubes, and/or ovaries.

sexually transmitted disease (STD) A illness caused by a pathogen that is transmitted from one person to another mainly through sexual contact.

syphilis An STD caused by the bacterium *Treponema pallidum.* In the U.S., about 70,000 new cases of syphilis occur each year.

Points to Consider

From fertilization to old age, the human body is like a fantastic machine. It controls its own growth and development, protects itself from dangers in the outside world and has amazing abilities to act, think, and feel. Like other living things, human beings are marvels of nature.

- What have you learned about human beings and other organisms by reading this book?

Image Sources

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Chapter 26

Appendix: Biology I

26.1 Investigation and Experimentation Activities

The following activities are based on information provided within this FlexBook or taken directly from the Teacher Edition.

Collecting and Analyzing Data

In this activity students will select and use appropriate tools and technology to perform tests, collect data, analyze relationships, and display data.

Students build skills in interpreting data and measuring through a simple activity. Have students measure a certain volume of water into a number of cups, such as 4 - 10 cups. Then have them first look online for what the threshold amount is for detecting sugar in water (see:http://www.skidmore.edu/~hfoley/Perc2.htm#ch2demo1).

Have one cup with water only (the control), and then have students add increasing amounts of sugar to each of the remaining cups. Keep track of the amount of sugar added. Have a person record for each student the threshold when that student detects the sugar (by taste) in the solution. The results are then tabulated and a graph made showing the number of students detecting the sugar solution at each concentration.

Experimental Error and Inconsistent Results

Students will identify and communicate sources of unavoidable experimental error and determine possible reasons for inconsistent results, such as sources of error or uncontrolled conditions.

As an extension to the above activity, have students conduct an experiment with the same

amount of sugar and water in each cup. Use an amount in which the sugar is detectable. Ask students to determine if there is the same or different amounts of sugar. Some students will determine that there are different amounts of sugar in the cups. Discuss the possible reasons for these results and how inconsistent results can influence collected data. You may choose to have one group of students set up the experiment for you (these students will not participate in the collection of data), with another group blind to the experimental conditions.

Experimental Error

An error is a boundary on the precision and accuracy of the result of a measurement. Some errors are caused by unpredictable changes in the measuring devices (such as balances, rulers, or calipers), but other errors can be caused by reading a measuring device incorrectly or by using broken or malfunctioning equipment. Such errors can have an impact on the reliability of the experiment's results; they affect the accuracy of measurements. For example, you use a balance to obtain the mass of a 100 gram block. Three measurements that you get are: 93.1 g, 92.0 g, and 91.8 g. The measurements are precise, as they are close together, but they are not accurate.

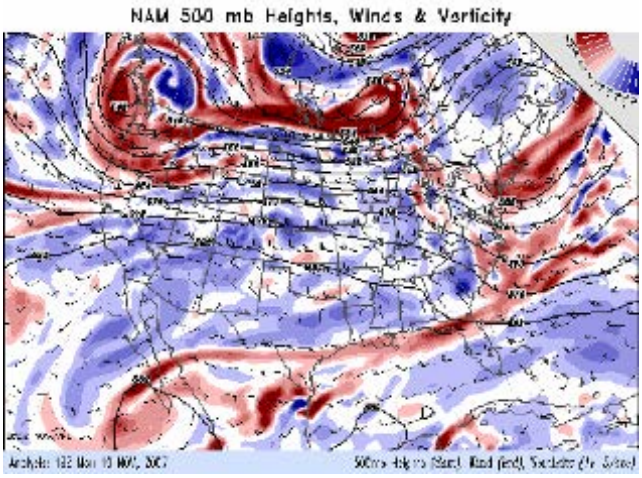
If the cause of the error can be identified, then it can usually be eliminated or minimized. Reducing the number of possible errors by careful measurement and using a large enough sample size to reduce the effect of errors will improve the reliability of your results.

Have students discuss potential opportunities for experimental error in the above activity, and have them describe how they could have affected the experimental results. Have the class discuss controls they could have added to this test to reduce experimental error.

Scientific Models

During this activity, students should realize that appropriate tools and technology (such as computer-linked probes, spreadsheets, and graphing calculators) are used to perform tests, collect data, analyze relationships, and display data. Throughout this activity, students should also recognize both the usefulness and limitations of scientific models, and that models are a scientific representations of reality.

Have the students look at the figure below and discuss: 1. What kind of model this is (computer). 2. What this model is used for (to forecast wind speeds and directions). 3. How this model might be useful (for example, weather forecasts; airline routes). 4. What is the main advantage of this visual model to the public (much easier to understand than a large table of numbers)? 5. Also ask the students how this model (and models in general) are of use to scientists (for example, reflecting reality, predicting future observations, ease of use and how it looks [for example, the colors used]).



A computer model of wind patterns across the continental United States for 19 November, 2007. This model is used to forecast wind speeds and directions. Data on wind speed, direction, and related data are entered into a computer which then produces this simulation. This visual model is much easier for a person to understand than a large table of numbers.

- Another model that might be worth researching and discussing is one for water flow in the Everglades (Florida). Some scientists are investigating how an increase in freshwater flow will affect patterns of organic matter as it is carried by the water and deposited downstream. If water flow is increased, this organic matter will be deposited in greater amounts in the estuarine ecotone and could lead to even higher rates of productivity in these areas. http://evergladesplan.org/images/water_flow_to_everglades.jpg

Scientific Logic

During this activity students will formulate explanations by using logic and evidence. They will also use appropriate tools and technology to display data.

Have students come up with data online or do their own activity to generate data. Have the activity illustrate the area of biological study known as physiology. Have students work in pairs. Have the students take turns taking their pulses after sitting (pulse at resting), and then after jumping up and down after a time period, perhaps one to two minutes. Take pulses at varying times after the activity; immediately after, one minute after, two minutes after, etc. Data could be examined in a number of ways; how resting pulse compares to pulse right after the activity, at varying times after the activity, how long it might take to get back to a resting pulse, the differences in pulses between boys and girls, how pulse rate increases with how much time a person jumps (one minute vs. two minutes, etc.). Data could be presented in either graph or table form, or both. Have students come to a conclusion based on their results. The conclusion should be based on their evidence and scientific logic.

Science and Math

During this activity students need to understand the relationship between science and math.

Using a hypothetical rabbit population at Hardy-Weinberg equilibrium, have students determine both the allele frequencies and the genotype frequencies. This rabbit population has 9 albino rabbits and 91 brown rabbits (42 homozygous and 49 heterozygous rabbits).

Solution

- Instructors: Sample answers to these questions will be provided upon request. **Please send an email to teachers-requests@ck12.org to request sample answers.**

Statistical Variability

Students will recognize the importance of statistical variability.

Biodiversity

Use activity 1 at the web site below to introduce the concept of biodiversity and how it is measured. In the activity, students calculate a diversity index for each of several different "habitats," represented by plastic bottles that contain a variety of different dried beans, seeds, or other small items. Then, based on its diversity index, students decide what type of real-world habitat each bottle "habitat" best represents.

- http://www.accessexcellence.org/AE/ATG/data/released/0534-KathyParis/index.php

In this activity students use math to calculate the diversity index of a selected habitat. The closer to 1 the diversity index is, the more diverse and healthy the habitat is.

Hypothesis vs. Theory

Ask students to develop a scientific hypothesis. They may use the activity below.

During this activity students should discuss the difference between their hypothesis and a scientific theory, describing why their hypothesis is not a theory. They should also appreciate the usefulness and limitations of theories as scientific representations of reality.

Formulating a Hypothesis

Have students who go to school in a city make observations of pigeons, as to feeding behavior, interactions between birds, etc. Based on the observations, have them come up with a testable research hypothesis. Ask them to describe data that would support or disprove the hypothesis. For students in a rural area, have them do something similar with ants (observable behavior here might be the ants' tracks). http://www.birds.cornell.edu/pigeonwatch

Scientific Theory

Scientific theories are hypotheses which have stood up to repeated attempts at falsification and are thus supported by a great deal of data and evidence. Some well known biological theories include the theory of evolution by natural selection, the cell theory (the idea that all organisms are made of cells), and the germ theory of disease (the idea that certain microbes cause certain diseases). The scientific community holds that a greater amount of evidence supports these ideas than contradicts them, and so they are referred to as theories.

In every day use, people often use the word theory to describe a guess or an opinion. For example, "I have a theory as to why the light bulb is not working." When used in this common way, "theory" does not have to be based on facts, it does not have to be based on a true description of reality. This usage of the word theory often leads to a misconception that can be best summed up by the phrase "It's not a fact, it's only a theory." In such everyday usage, the word is most similar to the term hypothesis.

Scientific theories are the equivalent of what in everyday speech we would refer to as facts. In principle, scientific theories are always subject to corrections or inclusion in another, wider theory. As a general rule for use of the term, theories tend to deal with broader sets of phenomena than do hypotheses, which usually deal with much more specific sets of phenomena or specific applications of a theory.

When Data Does Not Fit

Students will understand that some observations may be wrong or fraudulent, and that sometimes a theory can be wrong.

Refer students to the proposals of Jean-Baptiste Lamarck. He proposed that acquired characteristics could be inherited. Evidence did not support his mechanism for change, but Darwin shared his ideas of change in species.

A few websites are provided for additional information about Lamarck.

- http://www.ucmp.berkeley.edu/history/lamarck.html
- http://www.mnsu.edu/emuseum/information/biography/klmno/lemarck_jean.html

Maps

In this activity, students will learn the relationship between science and maps. Students should examine the maps below and determine what the data depicts.

Stabilizing Selection and Sickle-Cell Anemia

Stabilizing selection can lead to the preservation of harmful alleles. A famous example is sickle-cell anemia. The gene for Beta-hemoglobin - half of the oxygen-carrying protein in our blood - has two alleles, which we will call Hgb-A and Hgb-S. Individuals having two copies of the Hgb-S allele suffer from sickle-cell anemia, a potentially lethal disease in which sickled cells clog capillaries and cannot carry oxygen efficiently. In equatorial regions, individuals with two copies of Hgb-A become infected with *Plasmodium* parasites and often die from malaria. However, individuals with one copy of each allele (the heterozygous genotype) escape both causes of death; although they may experience slight sickling at high altitudes, they do not suffer from full-blown anemia, and malaria parasites cannot infect their red blood cells. Stabilizing selection has maintained the frequencies of both alleles, even though each is potentially lethal in the homozygous state.

Solution

- Instructors: Sample answers to these questions will be provided upon request. **Please send an email to teachers-requests@ck12.org to request sample answers.**

Analysis of Natural Phenomena

Through a series of activities, students will understand that the analysis of locations, sequences, or time intervals have played a significant role in the analysis of scientific data.

Virtual Age Dating

Assign the animated activity Virtual Age Dating at the web site below. Students will learn more about radioactive decay and radiometric dating of fossils and then simulate the collection and analysis of radiometric data. The activity includes questions for students to check their understanding as they proceed.

- http://www.indiana.edu/~ensiweb/virt.age.html

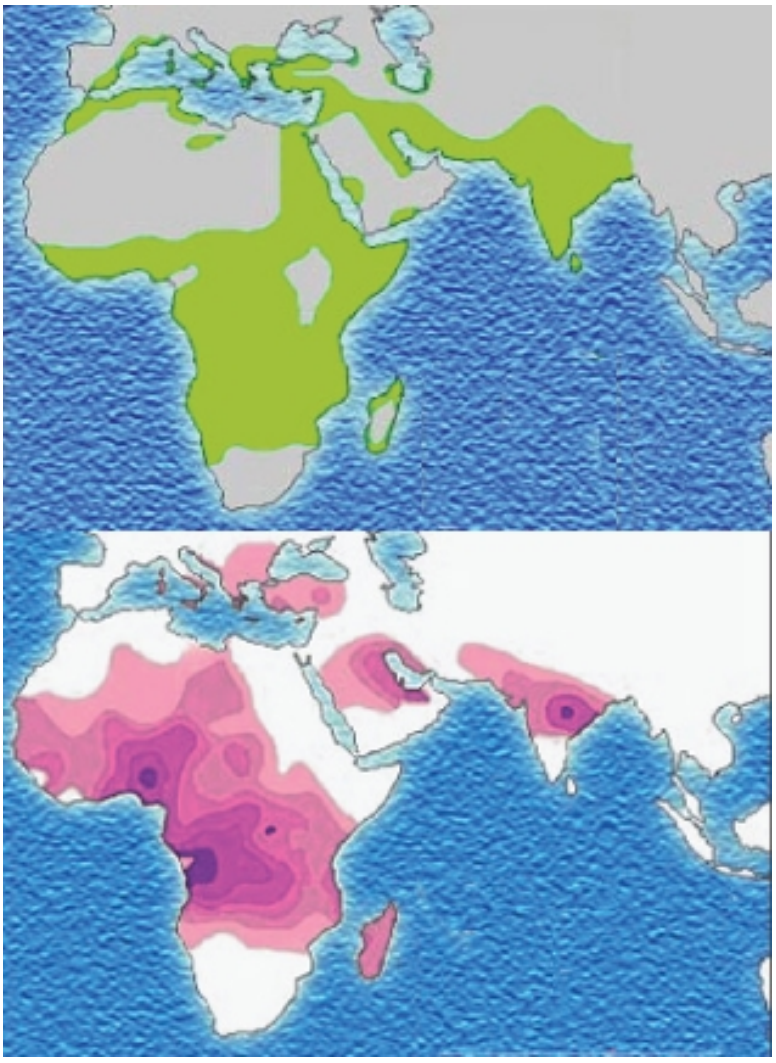


Figure 26.1: The distribution of malaria (top) and the distribution of the sickle-cell allele (bottom).

Geologic Timestring

Construct a geologic timestring (see URL below) that students can refer to as they read about evolution in this and subsequent lessons. The timestring is a physical representation of the geologic time scale. It is a simple tool that will help students comprehend the immensity of Earth's history and how recently life evolved.

- http://www.accessexcellence.org/AE/AEPC/WWC/1995/geo_time.php

Macroevolution: Patterns, Trends, and Rates of Change

After you discuss gradualism and punctuated equilibrium, ask students to complete the activity **Macroevolution: Patterns, Trends, and Rates of Change** (see URL below). In the activity, students will examine and graph patterns of fossil sequences and will decide whether the patterns support a gradualism or punctuated equilibrium model of evolution.

- http://www.indiana.edu/~ensiweb/lessons/macroev.html

An Accumulation of Evidence

Students will understand the cumulative nature of scientific evidence.

Evidence of Evolution

Refer students to Lesson 12.2: Evidence for Evolution.

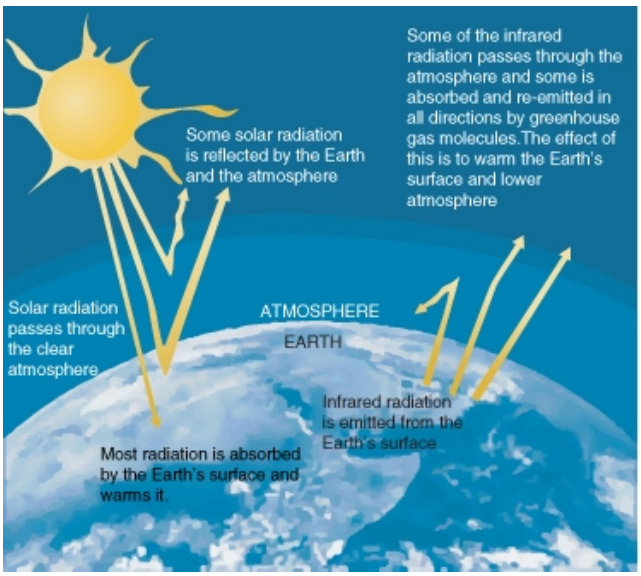
Have them create an outline of the lesson content or write an essay discussing the different types of evidence of evolution. All students should include a conclusion tying the evidence together, and discussion why this accumulation of evidence is a scientific theory.

Additional Scientific Disciplines

In this discussion and research project, students will analyze situations and solve problems that require combining and applying concepts from biology, ecology, chemistry and atmospheric sciences. Students will further investigate this extremely important issue.

Global Warming

Make sure students understand the greenhouse effect by working through the diagram in this **Figure** with the class.



Discuss how the greenhouse effect is related to global warming. Specifically, discuss the following points:

- What is the greenhouse effect?
- The greenhouse effect is a natural consequence of Earth's atmosphere. Why?
- Without the greenhouse effect, Earth's average temperature would be much lower. Why?
- Changes in Earth's atmosphere (especially increased CO_2) have increased the greenhouse effect and Earth's average temperature. How?

Have students continue this analysis with further research on this or a related topic. Students should research the literature, analyzing data that they find and communicate their findings to the class. Aspects of the greenhouse effect that may be further investigated include:

- potential issues for plants and animals associated with this effect
- any relationship between the greenhouse effect and global warming
- potential effects of global warming.