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Life Science

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Contents

Chapter 1

Studying Life

1.1 Lesson 1.1: The Nature of Science

Lesson Objectives

- Understand that science is a system based on evidence, testing, and reasoning.
- Describe what the life sciences are and some of the many life science specialties.
- Describe the scientific method and why it is important.
- Define the words "fact," "theory," and "hypothesis."
- Describe some of the tools of life science.
- Know that scientists are required to follow strict guidelines.

Check Your Understanding

- What do you expect to learn from this class?

Introduction

Before proceeding through this class, you need to realize a number of fundamental concepts of science. You need to:

- Know that science is a way of knowing about the physical world, based on observable evidence, testing predictions, and reasoning
- Understand that, in science, theories and knowledge are constantly tested and questioned.
- Know that, when new information conflicts with existing explanations, scientists modify their explanations to be consistent with all evidence.

- Understand that principles of philosophy and religion usually cannot be tested scientifically, because they are not based on observable evidence.
- Identify what the life sciences are and some of the many specialties
- Know the difference between scientific theory and fact.

These raise several interesting questions:

1. Why is modern science producing many more improvements in our lives than it did a hundred years ago? Modern science is based on evidence, inquiry and testing which have replaced personal beliefs, mythology and other biased sources of information.
2. Is there anything that science cannot explain? Yes there is. Questions about ethics (right and wrong) and belief in supernatural forces can not be explained through science.
3. How can we "think like scientists?" To think like a scientist, you would need to:
   (a) ask questions about the world around you and seek new evidence that will help answer questions,
   (b) base your understanding of the world on evidence, testing and reasoning instead of biased belief systems,
   (c) continuously question and test the accuracy of your knowledge and assumptions (including so-called "common sense").

Goals of Science

Science, religion, mythology, and magic share the goal of knowing about and explaining the world, such as the physical world, but their approaches are vastly different. The difference between them is their approach to "knowing." The vastness of the living, physical world includes all organisms (**Figure** 1.1), on land (**Figure** 1.2) and in the sea (**Figure** 1.3). As humans, some of the things we want to know and understand are what makes us healthy, what makes us sick, and how we can protect ourselves from floods, famine and drought.

Throughout history, humans have looked for ways to understand and explain the physical world. Try to imagine what humans thought about themselves and the world around them 1,000 years ago, or 5,000 years ago, or more. If you were born then, how would you have explained why the sun moved across the sky, then disappeared? How would you explain why your body changes as you grow, or birth and death? What explanation would you have for lightning, thunder, and storms?

Throughout time, different cultures have created hundreds of different myths and stories and even gods to explain what they saw. Ancient Greeks explained that lightning was a show of their god Zeus' anger. Scandinavians claimed that their god of thunder, Thor, was responsible for the rumbling and bolts of lightning. Without any formal science, many cultures have also blamed diseases, such as epilepsy, on evil spirits and other imaginary

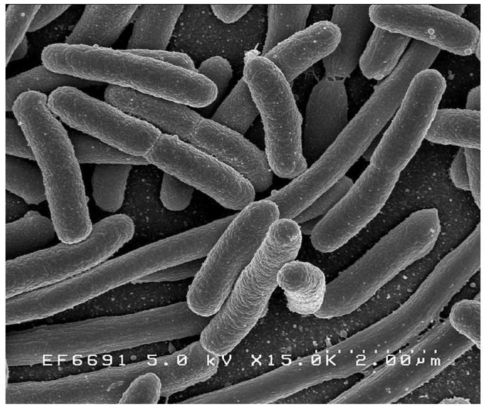

Figure 1.1: *Escherichia coli* bacteria (25)

Figure 1.2: A male lion. (9)

Figure 1.3: A Humpback whale. (15)

entities. For example, there is evidence that many different cultures drilled holes in the skulls of patients who had seizures or other maladies, thinking that they were releasing evil spirits.

Science as a Way of Knowing

During your own and your parents' lifetimes, advances in medicine (**Figure** 1.4), technology, and other fields have progressed faster than any other time in history. This explosion of advances in our lives is largely due to human use of modern science as a way of understanding. Today's scientists are trained to base their comprehension of the world on evidence and reasoning rather than belief and assumptions.

Figure 1.4: The anatomy lesson of Dr. Nicolaes Tulp. (26)

Modern science is:

- A way of understanding about the physical world, based on observable evidence, reasoning, and repeated testing.
- A body of knowledge that is based on observable evidence, experimentation, reasoning, and repeated testing.

As we learn more, new information occasionally conflicts with our current understanding. When this happens scientific explanations are revised. The **Figure** 1.5 demonstrates this. However, science cannot scrutinize what is good versus what is bad (morality), because these are values, ideas that lack measurable evidence. Science is not used to examine philosophy

Figure 1.5: In 1847, a doctor, Ignaz Semmelweis, demonstrated that when he washed his hands before delivering babies fewer women died from infection. Before this, doctors held untested beliefs about the causes of disease, such as a person's behavior, or the air they breathed. (5)

or supernatural entities, such as the existence or nonexistence of a god. However, science can be used to examine the effects of these experiences.

The most important message from this chapter is that science is not only a way of knowing it is also a way of thinking and reasoning. Scientists try to look at the world objectively - without bias or making assumptions. How? Scientists learn to be skeptical, to question the accuracy of our ideas. They learn to base their understanding of the physical world on evidence, reasoning and repeated testing of ideas.

To Think Like a Scientist

To think like a scientist, you need to be skeptical about and question your assumptions, including what often seems like common sense. Questioning ideas can often lead to surprising results. For example, if you ask people whether it's easier to keep a plastic cutting board clean or a wooden one clean, most people will think that the plastic board is easier to keep clean and has fewer germs (**Figure** 1.6).

Why do most people believe that plastic is safer? Probably because we assume that it is easier to wash germs off plastic than off wood. This assumption is promoted by the makers of plastic cutting boards and it sounds reasonable. After all, wood stains and looks unhygienic; plastic cutting boards come out of the dishwasher shiny and clean looking. But is plastic

Figure 1.6: Which is safer, a plastic or wood cutting board? (3)

actually better?

When scientists tested this idea, the answer turned out to be no. The researchers treated used cutting boards with different kinds of germs and then washed the boards. They found, much to their surprise, that gouged and sliced wooden cutting boards had far fewer germs than gouged and sliced plastic boards. The researchers discovered that germs that cause food poisoning, such as *E. coli* and *Salmonella*, are absorbed into the wood and seemed to vanish. On plastic, the germs sit on the surface in cuts in the plastic where they are difficult to clean out but can contaminate food. Furthermore, in a different study of food poisoning, people who used wooden cutting boards were less than half as likely to get sick as people using plastic ones.

”Common sense” may seem to have all the answers, but science is all about following the evidence. So what is good evidence? Evidence is information that can be used to confirm or refute an idea or to explain something. Both scientists and lawyers use evidence to support an idea or to show that an idea is probably wrong. Scientific evidence has certain features, which may be different from legal evidence.

Evidence is:

1. a direct, physical observation of a thing, a group of things, or of a process over time.
2. usually something measurable or ”quantifiable.”
3. the result of something.

For example, a book falling to the ground is evidence in support of the theory of gravity. A bear skeleton in the woods would be supporting evidence for the presence of bears.

What Are the Life Sciences?

The life sciences are the study of living organisms and how they interact with each other and their environment. These include all the biological sciences. Life sciences deal with every aspect of living organisms. The life sciences are so complex that most scientists focus on just one or two subspecialties — see tables 1.1, 1.2, and 1.3. Also, some focus on the relationship between living organisms, which is depicted in a phylogenetic "Tree of Life" (**Figure** 1.7).

Table 1.1: **Subspecialties that focus on one type of organism**

Subspecialty	Studies	Subspecialty	Studies
Botany	plants	**Zoology**	animals
Marine biology	organisms living in and around oceans, and seas	**Fresh water biology**	organisms living in and around freshwater lakes, streams, rivers, ponds, etc.
Microbiology	microorganisms	**Bacteriology**	bacteria
Virology	viruses	**Entomology**	insects
Taxonomy	the classification of organisms		

Table 1.2: **Fields of life sciences that examine the structure, function, growth, development and/or evolution of living things**

Life Science	What it Examines	Life Science	What it Examines
Cell biology	cells and their structures	**Anatomy**	the structures of animals
Morphology	the form and structure of living organisms	**Physiology**	the physical and chemical functions of tissues and organs
Immunology	the mechanisms inside organisms that protect them from disease and infection	**Neuroscience**	the nervous system
Developmental biology and embryology	the growth and development of plants and animals	**Genetics**	the genetic make up of all living organisms (heredity)
Biochemistry	the chemistry of living organisms	**Molecular biology**	biology at the molecular level
Epidemiology	how diseases arise and spread (**Figure** 26.3)		

Table 1.2: (continued)

Life Science	What it Examines	Life Science	What it Examines

Table 1.3: **Fields of biology that examine the distribution and interactions between organisms and their environments**

Life Science	What it Examines	Life Science	What it Examines
Ecology	how various organisms interact with their environments	**Biogeography**	the distribution of living organisms (**Figure** 1.9)
Population biology	the biodiversity, evolution, and environmental biology of populations of organisms		

Scientific Theories

Science theories are produced through repeated studies, usually performed and confirmed by many individuals. Scientific theories are well established and tested explanations of observations. These theories produce a body of knowledge about the physical world that is collected and tested through the scientific method (discussed in the Scientific Method lesson).

The word "theory" has a very different meaning in daily life than it does in science. When someone at school says, "I have a theory," they sometimes just mean a hunch or a guess. This everyday meaning for "theory" can confuse people when well-tested and widely accepted scientific theories are discussed by nonscientists. For example, the theory of evolution is a well-established scientific theory that some people incorrectly say is just a hunch.

A scientific theory is based on evidence and testing that supports the explanation. Scientific theories are so well studied and tested that it is extremely unlikely that new data will discredit them. The idea that matter is made up of atoms, evolution, and gravity are all scientific theories about how the world works that scientists accept as fundamental principles of basic science. However, any theory may be altered or revised to make it consistent with new evidence.

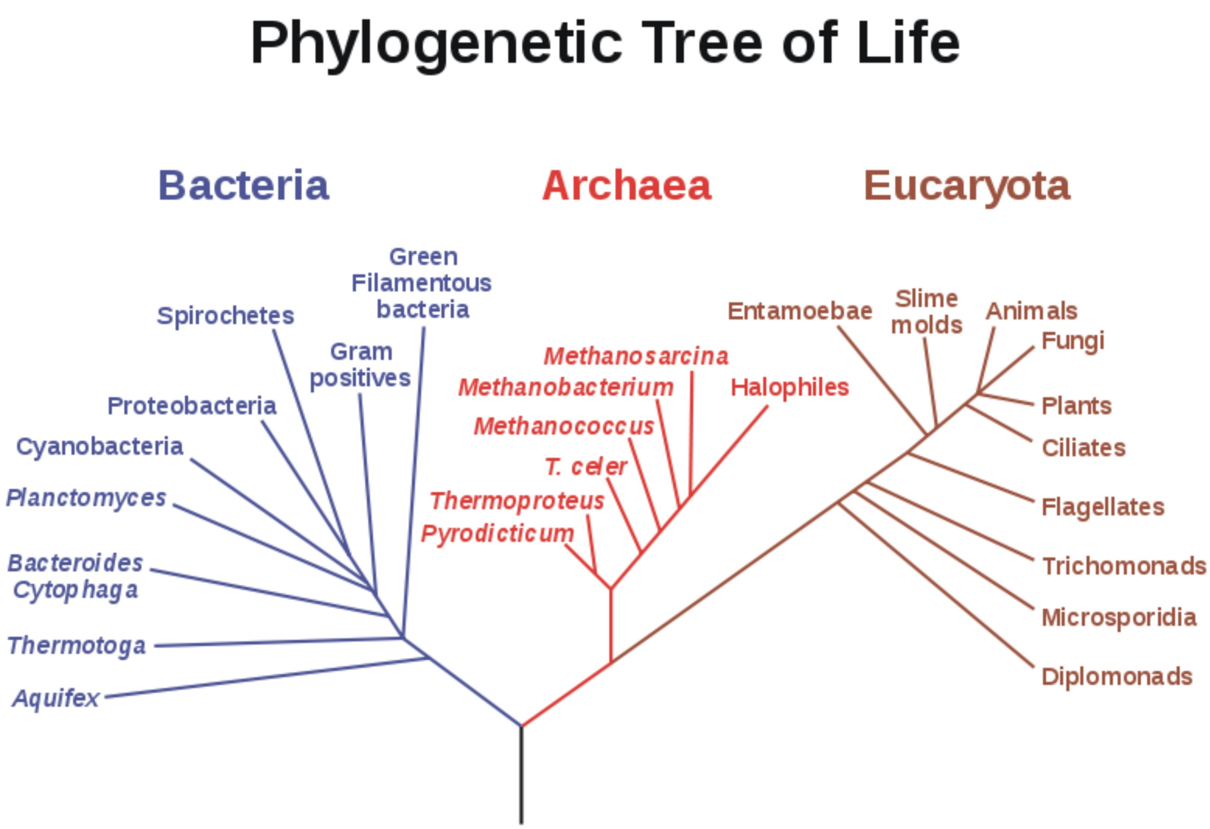

Figure 1.7: **The Phylogenetic Tree of Life** shows the relationship between living organisms. Humans and other mammals (eukaryotes) appear on the right side of the tree. The base of the tree represents the ancestor of all living organisms. (8)

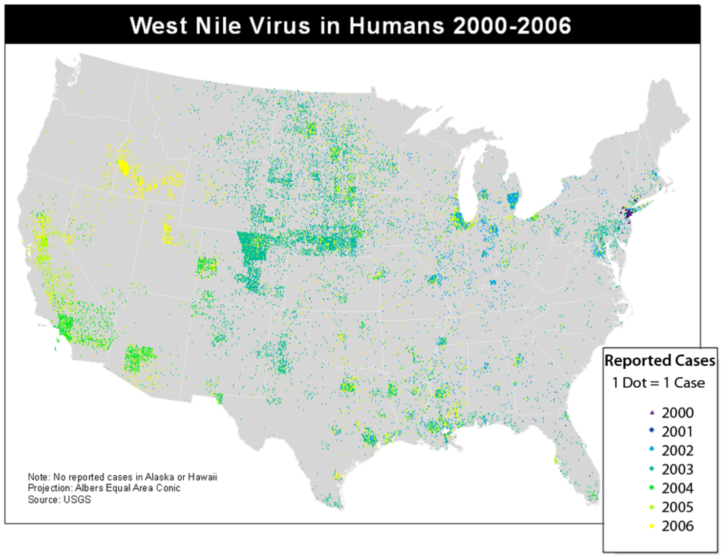

Figure 1.8: Epidemiologists study how diseases spread. The above map shows where humans contracted West Nile Virus between 2000 and 2006. It is believed the virus entered the United States in New York City in 1999. Notice how rapidly the virus spread across the U.S. (13)

Figure 1.9: Alexander von Humboldt mapped the distribution of plants across landscapes and recorded a variety of physical conditions such as pressure and temperature. Today, biogeographers study the diversity and distribution of organisms across Earth. (20)

Two Important Life Science Theories

In the many life sciences, there are possibly hundreds or thousands of theories. Yet there are at least two fundamental theories, which provide a foundation for modern biology. They are:

1. The Cell Theory
2. The Theory of Evolution

The Cell Theory

The Cell Theory states that:

- All organisms are composed of cells (**Figure** 1.10).

- Cells are the basic units of structure and function in an organism.
- Cells only come from preexisting cells; life comes from life.

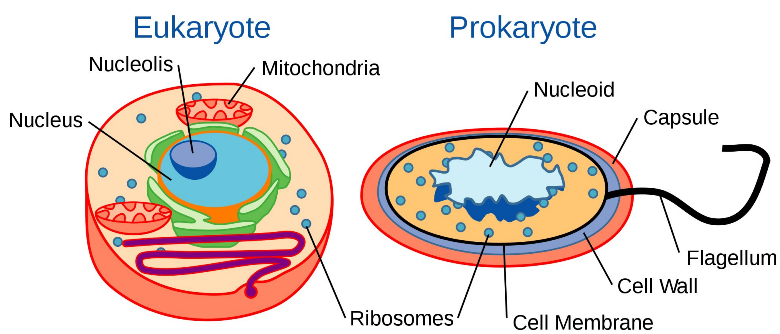

Figure 1.10: The two types of cells, eukaryotic (left) and prokaryotic (right). (10)

The development of the microscope in the mid 1600s made it possible to come up with this theory (**Figure** 1.11).

The Theory of Evolution

In biology, evolution is the process of change in the inherited traits of a population of organisms over time. Natural selection is the process where organisms that are better suited to the environment are more likely to survive and reproduce than others that are less suited to the environment. This theory basically states that better suited organisms live longer and have an easier time reproducing, passing on their traits that made them better suited

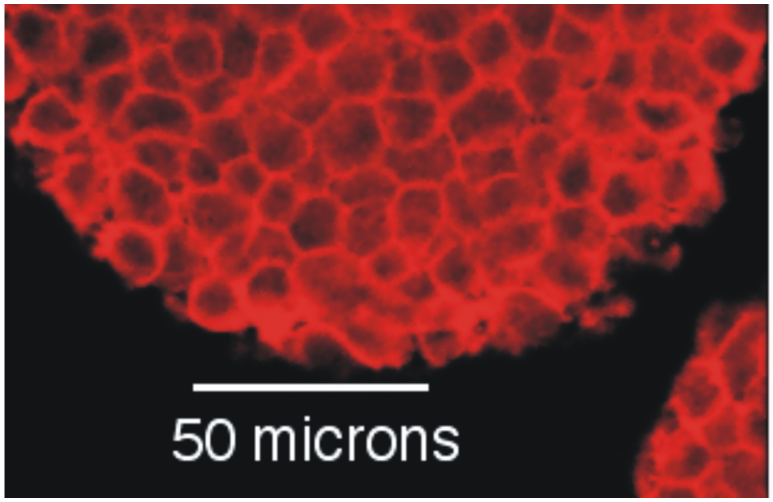

Figure 1.11: A mouse cell viewed through a microscope. (7)

to their environment. The theory of evolution by natural selection is often called the "great unifier" of biology, because it applies to every field of biology. It also explains the tremendous diversity and distribution of organisms across Earth. All living organisms (**Figure** 1.12 is a sampling) on Earth are descended from common ancestors.

Lesson Summary

- Science is a way of understanding (knowing) about the physical world that is based on evidence, reasoning, and testing predictions.
- A body of knowledge that has been thoroughly tested can still undergo further testing, and revisions as new evidence and questioning are raised.
- Science differs from other ways of knowing, because it is entirely based on observable evidence and its explanations are constantly questioned and tested.
- Science produces theories and general knowledge that allow us to better understand the world and to apply this knowledge to solve problems.

Review Questions

1. How is modern science different from other ways of knowing?
2. Explain why science cannot be used to examine whether someone is good or bad?
3. How is the scientific meaning of the word "theory" different from its use in day-to- day conversation?
4. What do all fields of life science have in common?
5. What are the three characteristics of evidence?
6. What is the goal of science?

Figure 1.12: Evolution explains the millions of varieties of organisms on Earth. (2)

7. What would you study if you were a biogeographer?

Further Reading / Supplemental Links

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Vocabulary

anecdotal evidence A description of an event that is used to make a point.

biogeography The study of the distribution of living organisms.

ecology The study of the interactions of organisms with each other and with their environment.

evidence Something that gives us grounds for knowing of the existence or presence of something else.

life science The study of living organisms and how they interact with each other and their environment.

population biology The study of the biodiversity, evolution, and environmental biology of populations of organisms.

science A way of knowing about the physical world, based on observable evidence, testing predictions, and reasoning.

science theories Well established and tested explanations of observations; produced through repeated studies, usually performed and confirmed by many individuals.

Points to Consider

- Next we are going to discuss the scientific method. You may have heard someone say that you can ruin your eyes if you sit too close to the television set.
- Describe how "thinking like a scientist" could help you figure out if this common sense idea is true or false.

1.2 Lesson 1.2: The Scientific Method

Lesson Objectives

- Consider how the scientific method is one of the most important reasons for how modern science is advancing more rapidly than in the past.
- Describe the scientific method as a process.
- Explain why the scientific method allows scientists and others to examine the physical world more objectively than other ways of knowing.
- Describe the steps involved in the scientific method.

Check Your Understanding

- What is science?
- What is a scientific theory?

Introduction

The **scientific method** is an inquiry process used to investigate the physical world using observable evidence and testing. This method allows scientists to "conduct" science in a uniform process. This process allows the information collected to be reproduced by other scientists, and most importantly, this process allows the information to be accepted and trusted.

Observations, Data, Hypotheses, and Experiments

Imagine that you are scientist who wants to know something like, "Why do whales migrate?" or "Why do some people get more colds than others do?" Two hundred years ago you could have come up with theories without necessarily thoroughly testing your ideas. But there were many exceptional scientists who made outstanding contributions. Here is a painting of Michael Faraday in his laboratory in the Royal Institution in England during the 1800s (**Figure** 1.13). Michael Faraday is best known for his contributions to chemistry, and he probably used some form of the scientific method to answer his questions.

Figure 1.13: Michael Faraday in his laboratory at the Royal Institution during the mid 1800s. (4)

As a modern scientist today, you would use the scientific method, collecting evidence to test your hypothesis and answer your questions. The scientific method presents a general idea of how science is conducted; it is not a strict pattern for doing research. Scientists use many different variations of the scientific method to meet their specific needs. Almost all versions of the scientific method include the following steps, though not always in the same order:

1. Make observations
2. Identify a question you would like to answer about the observation
3. Research: find out what is already known about your observation
4. Form a hypothesis
5. Test the hypothesis
6. Analyze your results
7. Communicate your results

A **hypothesis** is a proposed explanation that allows you to make predictions about what ought to happen if the hypothesis is true. If the predictions are accurate, that provides support for the hypothesis. If the predictions are incorrect, that suggests the hypothesis is wrong.

Make Observations

Observe something in which you are interested. Here is an example of a real observation made by students in Minnesota (**Figure** 26.1). Imagine that you are one of the students who discovered this strange frog.

Figure 1.14: A frog with an extra leg. (21)

Imagine that you are on a field trip to look at pond life. While collecting water samples, you notice a frog with five legs instead of four. As you start to look around, you discover that many of the frogs have extra limbs, extra eyes or no eyes. One frog even has limbs coming out of its mouth. You look at the water and the plants around the pond to see if there is anything else that is obviously unusual like a source of pollution.

Identify a Question That is Based on Your Observations

The next step is to ask a question about these frogs. For example, you may ask why so many frogs are deformed. You may wonder if there is something in their environment causing these defects. You could ask if deformities are caused by such materials as water pollution, pesticides, or something in the soil nearby (**Figure** 1.15).

Yet, you do not even know if this large number of deformities is "normal" for frogs. What if many of the frogs found in ponds and lakes all over the world have similar deformities? Before you look for causes, you need to find out if the number and kind of deformities is unusual. So besides finding out *why* the frogs are deformed, you should also ask:

“Is the percentage of deformed frogs in pond A (your pond) greater than the percentage of deformed frogs in other places?”

Figure 1.15: A pond with frogs. (14)

Research Existing Knowledge About the Topic

No matter what you observe, you need to find out what is already known about your topic. For example, is anyone else doing research on deformed frogs? If yes, what did they find out? Do you think that you should repeat their research to see if it can be duplicated? During your research, you might learn something that convinces you to alter your question.

Construct a Hypothesis

A hypothesis is a proposed explanation of an observation. For example, you might hypothesize that a certain pesticide is causing extra legs. If that’s true, then you can *predict* that the water in a pond of healthy non deformed frogs will have lower levels of that pesticide. That’s a prediction you can test by measuring pesticide levels in two sets of ponds, those with deformed frogs and those with nothing but healthy frogs. A hypothesis is an explanation that allows you to predict what results you will get in an experiment or survey.

The next step is to state the hypothesis formally. A hypothesis must be ”testable.”

Example:

After reading about what other scientists have learned about frog deformities, you predict what you will find in your research. You construct a hypothesis that will help you answer your first question.

Any hypothesis needs to be written in a way that it can:

1. Be tested using evidence.
2. Be falsified (found false/wrong).
3. Provide measurable results.
4. Provide yes or no answers.

For example, the following hypothesis can be tested and provides yes or no answers:

"The percentage of deformed frogs in five ponds that are heavily polluted with a specific chemical X is higher than the percentage of deformed frogs in five ponds without chemical X."

Test Your Hypothesis

The next step is to count the healthy and deformed frogs and measure the amount of chemical X in all the ponds. This study will test the hypothesis. The hypothesis will be either true or false.

An example of a hypothesis that is not testable would be: "The frogs are deformed because someone cast a magic spell on them." You cannot make any predictions based on the deformity being caused by magic, so there is no way to test a magic hypothesis or to measure any results of magic. There is no way to prove that it is not magic, so that hypothesis is untestable and therefore not interesting to a scientist.

Analyze Data and Draw a Conclusion

If a hypothesis and experiment are well designed, the experiment will produce measurable results that you can collect and analyze. The analysis should tell you if the hypothesis is true or false.

Example:

Your results show that pesticide levels in the two sets of ponds are statistically different, but the number of deformed frogs is almost the same when you average all the ponds together. Your results demonstrate that your hypothesis is either false or the situation is more complicated than you thought. This gives you new information that will help you decide what to do next. Even if the results supported your hypothesis, you would probably ask a new question to try to better understand what is happening to the frogs and why. When you are satisfied that you have accurate information, you share your results with others.

You will probably revise your hypothesis and design additional experiments along the way.

Communicate Results

Scientists communicate their findings in a variety of ways. For example, they may discuss their results with colleagues, talk to small groups of scientists, give talks at large scientific meetings, and write articles for scientific journals. Their findings may also be communicated to journalists.

Example:

You eventually decide that you have strong results to share about frog deformities. You write an article and give talks about your research. Your results could contribute towards solutions.

Drawing Conclusions and Communicating Results

If a hypothesis and experiment are well designed, the results will indicate whether your hypothesis is true or false. If a hypothesis is supported by the results of a study, scientists will often continuing testing the hypothesis in new ways to learn more.

If a hypothesis is false, the results may be used to construct and test a new hypothesis. The next step is to analyze your results and to communicate them to other scientists. Scientific articles include the questions, methods and the conclusions from their research. Other scientists may try to repeat the experiments or change them. Scientists spend much time sharing and discussing their ideas with each other. Different scientists have different kinds of expertise they can use to help each other. When many scientists have independently come to the same conclusions, a scientific theory is developed. A scientific theory is a well-established explanation of an observation. In is generally accepted among the scientific community. Scientific theories are discussed in *The Nature of Science* Lesson.

Basic and Applied Science

Science can be "basic" or "applied." The goal of basic science is to understand how things work - whether it's why things fall on the floor or the structure of cells. Basic science is the source of most scientific theory and new knowledge. Applied science is using scientific discoveries to solve practical problems or to create new technologies.

Even though basic research is not intended to solve problems directly, basic research always provides the knowledge that applied scientists need to solve problems. For example, medicine and all that is known about how to treat patients is applied science based on basic research (**Figure** 1.16).

Figure 1.16: A healthy newborn being examined by a doctor. (23)

Lesson Summary

- The scientific method is an inquiry process used to investigate the physical world using observable evidence and testing.
- A hypothesis is a proposed explanation of an observation; it is used to test an idea.
- A theory is a well-established explanation of an observation. A hypothesis must be written in a way that can be tested, is falsifiable (to be able to prove that something is false), is measurable, and will help answer the original question.

Review Questions

1. How is a hypothesis different from a theory?
2. What does a hypothesis need to include?
3. What does "falsifiable" mean?
4. List the steps of the Scientific Method?
5. What is basic research?
6. What is applied research?
7. What does a scientist do if their research results conflict with previous theories or popular knowledge?
8. Is it OK for scientists to change their ideas?

Further Reading / Supplemental Links

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Vocabulary

applied science The application of science to practical problems.

basic science Research whose goal is just to find out how the world works, not to solve an urgent problem. Basic research is the source of most new scientific information and nearly all new theories.

falsifiable Testable. If a hypothesis generates predictions that can be shown to be true or false by experiment or observation, the hypothesis is ”falsifiable” or ”testable.”

hypothesis A proposed explanation for something that is testable.

predict To say what will happen in a given situation. A scientific prediction is different from an everyday prediction, like predicting the weather before it happens. A scientific prediction is related to a specific hypothesis.

scientific method A careful way of asking and answering questions to learn about the physical world that is based on reason and observable evidence.

scientific theory A well-established set of explanations that explain a large amount of scientific information.

Points to Consider

- Next we consider the tools of the scientist.
- How do you think scientific “tools” can help a scientist?
- What do you think is one of the more common tools of the life scientist?

1.3 Lesson 1.3: Tools of Science

Lesson Objectives

- Describe the growing number of tools available to investigate different features of the physical world.
- Describe how microscopes have allowed humans to view increasingly small tissues and organisms that were never visible before.

Check Your Understanding

- What is the scientific method?
- What is an experiment?

Using Microscopes

Microscopes, tools that you may get to use in your class, are some of the most important tools in biology **Figure** 1.17 . Before microscopes were invented in 1595, the smallest things you could see on yourself were the tiny lines in your skin. The magnifying glass, a simple glass lens, was developed about 1200 years ago. A typical magnifying glass may have doubled the size of an image. But microscopes allowed people to see objects as small as individual cells and even large bacteria. Microscopes let people see that all organisms are made of cells. Without microscopes, some of the most important discoveries in science would have been impossible.

Microscopes are used to look at things that are too small to be seen by the unaided eye. **Microscopy** is a technology for studying small objects using microscopes. A microscope that magnifies something two to ten times (indicated by 2X or 10X on the side of the lens) may be enough to dissect a plant or look closely at an insect. Using even more powerful microscopes, scientists can magnify objects to two million times their real size.

Some of the very best early optical microscopes were made four hundred years ago by Antoine van Leeuwenhoek (**Figure** 1.18), a man who taught himself to make his own microscopes (**Figure** 1.19). When he looked at a sample of scum from his own teeth, Leeuwenhoek discovered bacteria. In rainwater, he saw tiny protozoa. Imagine his excitement when he looked through the microscope and saw this lively microscopic world. van Leeuwenhoek discovered the first one-celled organisms (protists), the first bacteria, and the first sperm. Robert Hooke, an English natural scientist of the same period of history, used a microscope to see and name the first ”cells” (**Figure** 1.20), which he discovered in plants.

Some modern microscopes use light, as Hooke’s and van Leeuwenhoek’s did, but others may use electron beams or sound waves.

Researchers now use four kinds of microscopes:

1. **Light microscopes** allow biologists to see small details of biological specimens. Most of the microscopes used in schools and laboratories are light microscopes. Light microscopes use refractive lenses, typically made of glass or plastic, to focus light either into the eye, a camera, or some other light detector. The most powerful light microscopes can magnify images up to 2,000 times. Light microscopes are not as powerful as other higher tech microscopes but they are much cheaper and anyone can own one and see many amazing things.
2. **Transmission electron microscopes** (TEM) focus a beam of electrons through an

Figure 1.17: Basic light microscopes opened up a new world to curious people. 1, ocular lens or eyepiece; 2, objective turret; 3, objective lenses; 4, coarse adjustment knob; 5, fine adjustment knob; 6, object holder or stage; 7, mirror or light (illuminator); 8, diaphragm and condenser. (11)

Figure 1.18: Antoine van Leeuwenhoek, a Dutch cloth merchant with a passion for microscopy. (1)

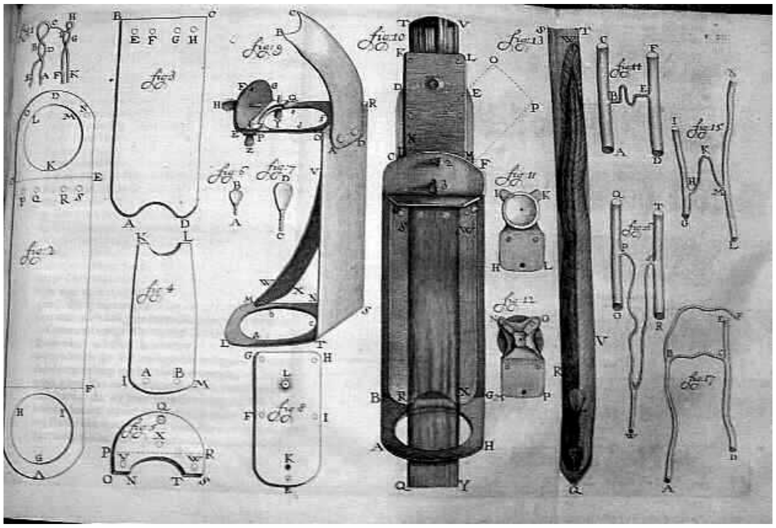

Figure 1.19: Drawing of microscopes owned by Antoine van Leeuwenhoek. Bacteria were discovered in 1683 when Antoine Van Leeuwenhoek used a microscope he built to look at the plaque on his own teeth. (12)

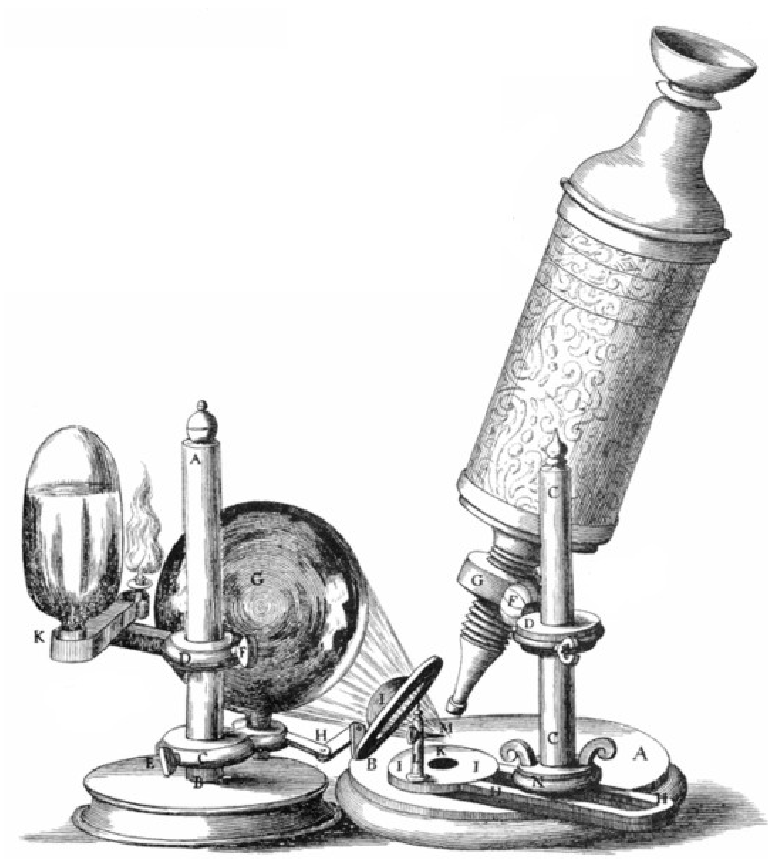

Figure 1.20: Robert Hooke's early microscope. (19)

object and can magnify an image up to two million times with a very clear image ("high resolution").

3. **Scanning electron microscopes** (SEM) (**Figure** 1.21) allow scientists to map the surfaces of extremely small objects. These microscopes slide a beam of electrons across the surface of specimen, producing detailed maps of the shapes of objects.
4. **Scanning acoustic microscopes** use sound waves to scan a specimen. These microscopes are useful in biology and medical research.

Figure 1.21: A scanning electron microscope. (6)

Other Life Science Tools

What other kinds of tools and instruments would you expect to find in a biologist's laboratory or field station? Other than computers and lab notebooks, biologists use very different instruments and tools for the wide range of life science specialties. For example, a medical research laboratory and a marine biology field station might not use any of the same tools. Tools such as a radiotelemetry device (**Figure** 1.22), or a thermocycler (**Figure** 1.23) and even a fume hood (**Figure** 1.24) are all biological equipment.

Figure 1.22: A radiotelemetry device used to track the movement of seals in the wild. (22)

Using Maps and Other Models

You use models for many purposes. A volcano model, is not the same as a volcano, but it is useful for thinking about real volcanoes. We use street maps to represent where streets are in relation to each other. A model of planets may show the relationship between the positions of planets in space. Biologists use many different kinds of models to simulate real events and processes. Models are often useful to explain observations and to make scientific predictions.

Some models are used to show the relationship between different variables. For example, the model in **Figure** 26.4 says that when there are few coyotes, there are lots of rabbits (left side of the graph) and when there are only a few rabbits, there are lots of coyotes (right side of the graph). You could make a prediction, based on this model, that removing all the coyotes from this system would result in an increase in rabbits. That's a prediction that can be tested.

Figure 1.23: A thermocycler used for molecular biological and genetic studies. (17)

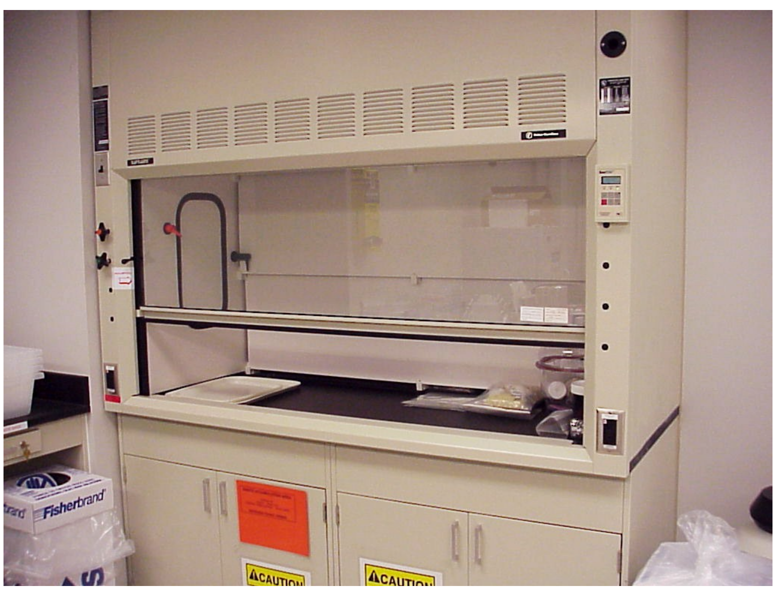

Figure 1.24: A laboratory fume hood. This laboratory hood sucks dangerous fumes out of a lab and allows researchers to work with dangerous chemicals without breathing them. (27)

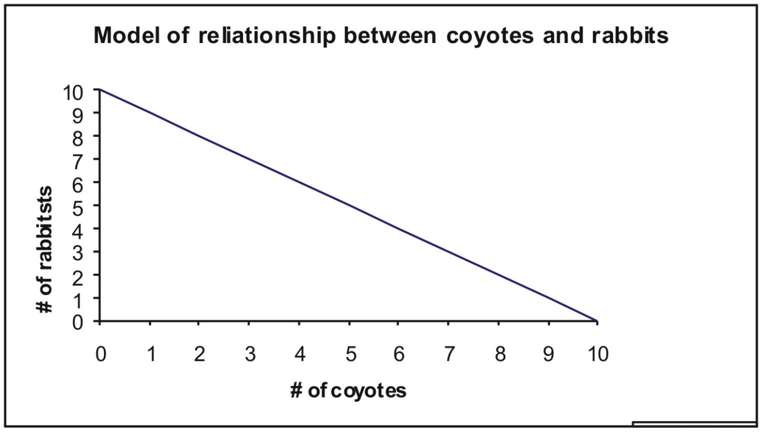

Figure 1.25: This graph shows a model of a relationship between a population of coyotes (the predators) and a population of rabbit, which the coyotes are known to eat (the prey). (18)

Lesson Summary

- From the time that the first microscope was built, over four hundred years ago, microscopes have been used to make major discoveries.
- Life science is a vast field; different kinds of research usually require very different tools.
- Basic research produces knowledge and theories; applied research uses knowledge and theories from basic research to develop solutions to practical problems.
- Scientists use maps and models to understand how features of real events or processes work.

Review Questions

1. What did van Leeuwenhoek discover when he looked at plaque from his own teeth under the microscope?
2. What does the symbol 10X on the side of a microscope mean?
3. What is a scientific model?
4. Look at the predator/prey (coyote/rabbit) model again. What does the model predict would happen to the rabbit population if you took away all the coyotes?
5. How long ago were the first microscopes invented?
6. What tool would you use to keep track of where a wolf travels?
7. What is the relationship between basic and applied research?

Vocabulary

applied research Research designed for the purpose of producing results that may be applied to real world situations.

basic research Research to gain new knowledge about the basic processes of life, including how the body works; but the goal is not a commercial application.

electron microscopes Used to create high magnification (magnified many times) and high resolution (very clear) images.

microscopes A set of lenses used to look at things too small to be seen by the unaided eye.

microscopy All the methods for studying things using microscopes.

optical (light) microscopes A microscope that focuses light, usually through a glass lens; used by biologists to small details of biological specimens.

scanning acoustic microscopes A microscope that focuses sound waves instead of light.

scanning electron microscopes A microscope that scans the surfaces of objects with a beam of electrons to produce detailed images of the surfaces of tiny things.

Points to Consider

- What could be some hazards that biologists may face in the laboratory?
- What could be risks of doing field research?
- So what do you think biologists do to protect themselves?

1.4 Lesson 1.4: Safety in Scientific Research

Lesson Objectives

- Recognize how the kind of hazards that a scientist faces depends on the kind of research they do.
- Identify some potential risks associated with scientific research.
- Identify who and what safety regulations are designed to protect.

Check Your Understanding

- What is the scientific method?

Introduction

There are some very serious safety risks in scientific research. Research can involve many different kinds of risks. Yet, if science were as dangerous as some horror movies make it look, not many people would become scientists. Since the life sciences deal with living organisms, some research may have risks not found in other fields. Safety practices are needed to work with any potentially hazardous situation, such as:

- pathogenic (disease-causing) viruses, bacteria or fungi
- parasites
- wild animals
- radioactive materials
- pollutants in air, water, or soil
- toxins
- teratogens
- carcinogens
- radiation

The kinds of risks that scientists face depend on the kind of research they perform. For example, a bacteriologist working with bacteria in a laboratory faces different risks than a zoologist studying the behavior of lions in Africa. Think back to the deformed frogs discussed earlier, the ones in the pond with extra limbs or extra eyes. If there is something in the frogs' environment causing these deformities, could there be a risk to a researcher in that environment? A chemical in the pond that could cause such deformities is called a "teratogen." Or perhaps a disease is causing the deformities. Infectious agents such as viruses and bacteria are called **biohazards** (**Figure** 1.26). Biohazards include any material such as medical waste that could possibly transmit an infectious disease. A used hypodermic needle or a vial of bacteria are both biohazards.

Laboratory Safety

Most laboratories are safe places to visit. If you plan to work in a scientific laboratory, ask someone to tell you about the safety rules they are required to follow. Scientists must follow regulations set by federal, state, and private institutions. For example, scientists cannot work with hazardous materials or equipment without:

- Getting approval to do the specific research.

Figure 1.26: The Biohazard symbol. (24)

- Using safety equipment, such as hoods and fans (**Figure** 1.27 and **Figure** 1.28).
- Demonstrating that the staff are familiar with risks, know how to respond to problems, and can follow safety regulations.
- Accepting laboratory inspections by safety officers at any time.

Figure 1.27: An example of a science laboratory workbench. A fume hood is on the left. (28)

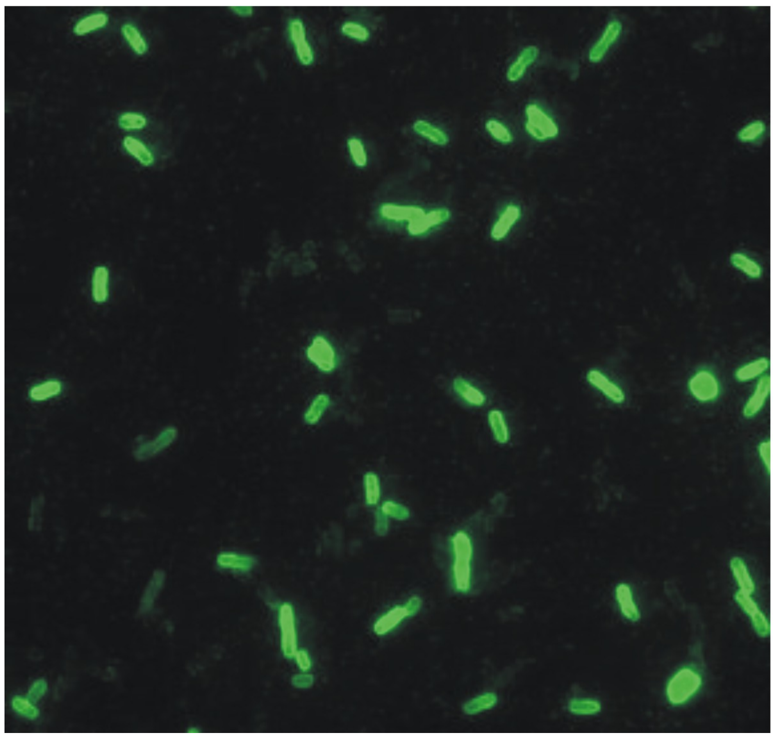

Figure 1.28: Scientists studying dangerous organisms such as *Yersinia pestis*, the cause of bubonic plague, use special equipment that helps keep the organism from escaping the lab. (16)

Field Research Safety

Scientists who work in the outdoors, called "field scientists," are also required to follow safety regulations designed to prevent harm to themselves, other humans, to animals, and the environment.

Scientists are required to follow the same level of safety standards in the field as they do in a laboratory. In fact, if scientists work outside the country, they are required to learn about and follow the laws and restrictions of the country in which they are doing research. For example, entomologists following monarch butterfly (**Figure** 1.29) migrations between the United States and Mexico would have to follow regulations in both countries.

Figure 1.29: A Monarch Butterfly (29)

Field scientists are also required to follow laws to protect the environment. Before biologists can study protected wildlife or plant species, they must apply for permission to do so, and obtain a research permit, if required.

Lesson Summary

- Research of any kind may have safety risks. Because biologists study living organisms as diverse as bacteria and bears, they deal with risks that other scientists may never encounter.
- The risks scientists face depend on the kind of research they are doing.
- Scientists are required by federal, state, and local institutions to follow strict regulations designed to protect the safety of themselves, the public, and the environment.

Review Questions

1. What kinds of hazards might be found in biology laboratories, but not physics laboratories?
2. Who has more freedom to do whatever research they want? Laboratory scientists or field biologists?
3. What is a biohazard?
4. What is a research permit?
5. What are some of the precautions you might take if you were collecting frogs in water you think might be polluted?
6. Name some possible hazards to field biologists.
7. If a scientist does research in a foreign country, which research laws would the scientist need to follow: those of the homeland or the foreign country?

Further Reading / Supplemental Links

Biosafety in Microbiological and Biomedical Laboratories (National Research Council, 1999).

Chemical Classification Signs:

- http://www.howe.k12.ok.us/~jimaskew/nfpa.htm

NFPA Chemical Hazard Labels:

- http://www.atsdr.cdc.gov/NFPA/nfpa_label.html

Where to Find MSDS's on the Internet:

- http://www.ilpi.com/msds/index.html

Cornell University MSDS:

- http://msds.pdc.cornell.edu/msdssrch.asp

MSDS Power Point:

- http://www.tenet.edu/teks/science/safety/pdf/hazcom/msds.ppt

- http://www.research.northwestern.edu/ors/biosafe/index.htm

Vocabulary

anecdotal evidence A description of an event that is used to make a point.

applied research Research designed for the purpose of producing results that may be applied to real world situations.

basic research Research to gain new knowledge about the basic processes of life, including how the body works normally; but the goal is not a commercial application.

biohazard Is any biological material, such as infectious material that poses a potential to human health, animal health, or the environment.

evidence Something used to clearly determine or demonstrate the truth of an assertion.

falsifiable Confirmable; capable of being tested (verified or falsified) by experiment or observation.

hypothesis A concept that is not yet verified but that if true would explain certain facts or phenomena.

pathogen A disease causing agent.

scientific model Something used to represent feature a real system or item.

theory An explanation for an event that is based on observation, experimentation, and reasoning.

Points to Consider

- We are now moving into examining living things.
- What do you think makes something "alive?"
- What may be some things a blade of grass, a fly, and you have in common?

Image Sources

(1) http://en.wikipedia.org/wiki/Image:Antoni_van_Leeuwenhoek.png. Public Domain.

(2) *Evolution explains the millions of varieties of organisms on Earth.*. CC-BY-SA 3.0.

(3) http://en.wikipedia.org/wiki/File:Chopping_Board.jpg. GNU-FDL.

(4) *M_Faraday_Lab_H_Moore.jpg* . Public Domain.

(5) Robert A. Thom. *[Wikipedia]*. Public Domain.

(6) *A scanning electron microscope.*. GNU-FDL.

(7) *A mouse cell viewed through a microscope.*. GNU-FDL.

(8) NASA. ***The Phylogenetic Tree of Life***. Public Domain.

(9) *A male lion.*. CC-BY 2.0.

(10) NCBI. http://commons.wikimedia.org/wiki/File:Celltypes.svg. Public Domain.

(11) http://en.wikipedia.org/wiki/Image:Optical_microscope_nikon_alphaphot.jpg. Public Domain.

(12) http://en.wikipedia.org/wiki/Image:Van_Leeuwenhoek%27s_microscopes_by_Henry_Baker.jpg. Public Domain.

(13) USGS. http://en.wikipedia.org/wiki/Image:WNVUSAMap.png. GNU-FDL.

(14) *A pond with frogs.*. GNU-FDL.

(15) *A Humpback whale.*. GNU Free Documentation.

(16) http://en.wikipedia.org/wiki/Black_Death. Public Domain.

(17) http://commons.wikimedia.org/wiki/Image:Pcr_machine.jpg. Public Domain.

(18) Talia Karasov. . CC-BY-SA.

(19) *Robert Hooke's early microscope.*. Public Domain.

(20) *Humboldt1805-chimborazo.jpg* . Public Domain.

(21) USGS. *A frog with an extra leg.*. Public Domain.

(22) http://en.wikipedia.org/wiki/File:Phoca_vitulina_Telemetry.jpg. CC-BY-SA 2.5.

(23) *A healthy newborn being examined by a doctor.*. GNU-FDL.

(24) *The Biohazard symbol.*. Public Domain.

(25) NIH. Escherichia coli *bacteria*. Public Domain.

(26) *The_Anatomy_Lesson.jpg* . Public Domain.

(27) `http://commons.wikimedia.org/wiki/File:Fume_hood.jpg`. Public Domain.

(28) `http://upload.wikimedia.org/wikipedia/commons/5/5f/Lab_bench.jpg`. CC-BY 1.0.

(29) Derek Ramsey. *A Monarch Butterfly*. GNU-FDL.

Chapter 2

Introduction to Living Organisms

2.1 Lesson 2.1: What are Living Things?

Lesson Objectives

- List the defining characteristics of living things.
- List the needs of all living things.

Check Your Understanding

- How do life scientists study the natural world?
- Are scientific theories just a ”hunch” or a hypothesis?

Introduction

How would you define a living thing? In other words, what do mushrooms, daisies, cats, and bacteria have in common? (The series of pictures in the **Figure** 2.1 are additional representations.) All of these are living things, or **organisms.** It might seem hard to think of similarities among such diverse organisms, but there are actually many similarities. The chemical processes inside all organisms are the same. For example, all living things encode their genetic information in the same way. And many organisms share the same needs, such as the need for energy and materials to build their bodies. Living things have so many similarities because all living things have evolved from the same common ancestor that lived billions of years ago.

All living organisms:

- Need energy to carry out life processes
- Are composed of one or more cells (the cell theory)
- Evolve and share an evolutionary history
- Respond to their environment
- Grow, reproduce themselves, and pass on information to their offspring in the form of genes
- Maintain a stable internal environment (homeostasis)

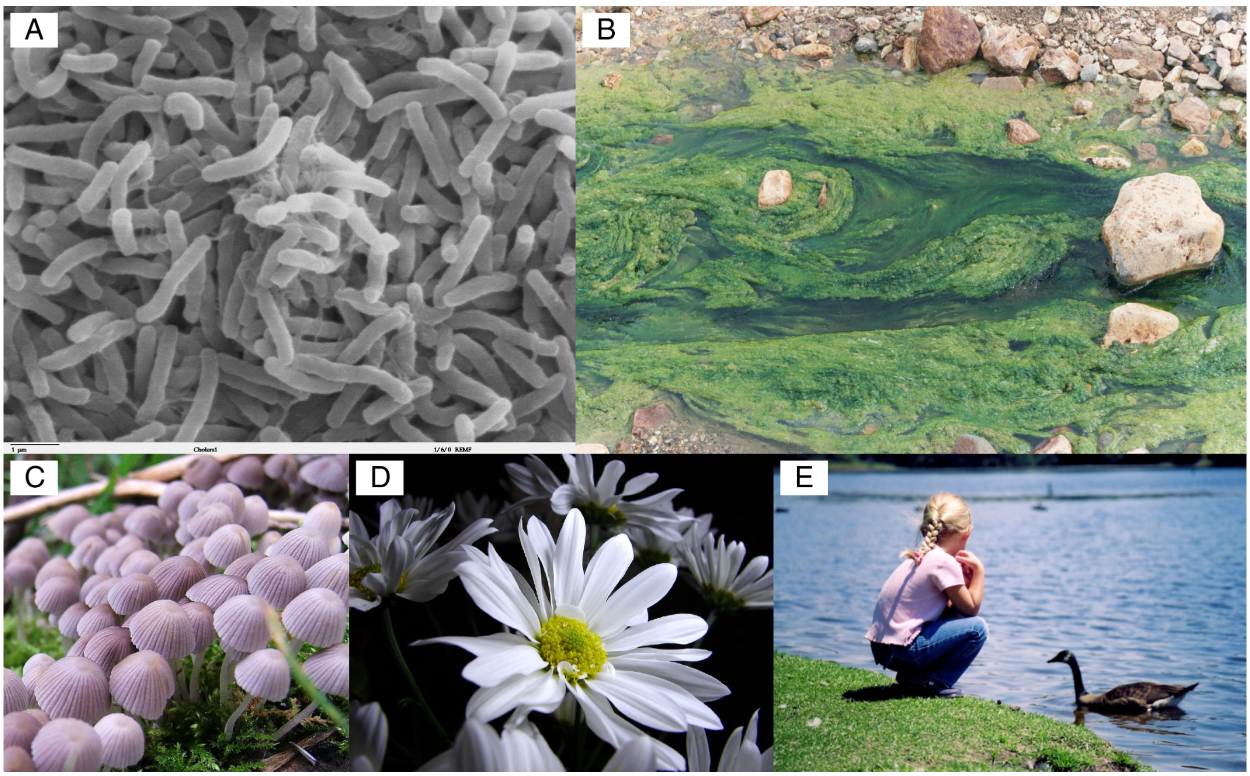

Figure 2.1: Life on Earth is very diverse, yet all these forms of life share some characteristics. Forms of life include: A) Bacteria, B) Algae, C) Fungi, D) Plants, and E) Animals. (13)

Living Things Maintain Stable Internal Conditions

All living things have some ability to maintain a stable internal environment. The inside of an organism is separate and different from the outside world. Maintaining that separation and difference is known as **homeostasis.** For example, many animals work hard to keep their temperature within a certain range. If the animal gets too hot or too cold, it will die. As a result, many animals have evolved behaviors that regulate their internal temperature. A lizard may stretch out on a sunny rock to increase its internal temperature, and a bird may fluff its feathers to stay warm (**Figure** 2.2).

Figure 2.2: A bird fluffs his feathers to stay warm (keep from losing energy) and to maintain homeostasis. (6)

Mammals and birds are **homeotherms**–meaning they maintain the same temperature most of the time. A lizard or an earthworm is a **heterotherm**, meaning its temperature can change.

Humans and other mammals may deliberately do things to stay warm or to cool off, like lie down under a shady tree. But most mammals maintain a steady temperature primarily through unconscious processes. A portion of your unconscious brain regulates your body temperature. If you get too warm, you start to sweat and the blood vessels in your skin open up to let the blood flow to the surface of your body. If you are too cold, you start to shiver and the blood supply to your skin, hands and feet may be reduced.

There are many forms of homeostasis besides temperature regulation. For example, when you have a big lunch, your body produces the hormone insulin, which helps maintain the right amount of sugar in your blood. Meanwhile, your kidneys are hard at work maintaining the right amount of water and salts in your blood. Both of these processes happen unconsciously and are part of homeostasis.

Living Things Grow and Reproduce

All living things reproduce. Organisms that do not reproduce go extinct, every time. As a result, there are no species that do not reproduce.

Reproduction, the process of creating a new organism, is different for different organisms. Many organisms reproduce sexually, where an egg and sperm go together to form a new

Figure 2.3: Like all living things, cats reproduce themselves and make a new generation of cats. When animals and plants reproduce they make tiny undeveloped versions of themselves called **embryos**, which grow up and develop into adults. A kitten is a partly developed cat. (22)

individual. (Cats are one such species, **Figure** 2.3.) Other organisms can reproduce without sex ("asexually"). For example, bacteria can simply split in two, producing two identical new cells. But it's not just bacteria that can reproduce without sex. Some lizards can produce clones of themselves. In such species, all individuals are female and simply lay their eggs when they are ready to reproduce. During all reproduction, the parents pass genetic information to their offspring, a process called **heredity**. Heredity is the passing of genes to the next generation. These genes influence all the traits of an organism, including overall body shape, size, whether it has fur or feathers, teeth or a beak, eye color, and so on. This genetic information is essential to an organism. In all organisms made of cells, this genetic information comes in the form of **deoxyribonucleic acid**, or DNA, which we will discuss in lesson 2. (In viruses, which are not made of cells, the genetic information is sometimes in the form of RNA, a different nucleic acid.) DNA contains the "instructions" for building important molecules inside of cells.

Living Things are Composed of Cells

All living things are composed of cells (**Figure** 2.4), the tiny units that are the building blocks of life. Cells are the smallest possible unit of life that is still considered living. Most cells are so small that they are usually visible only through a microscope. Some organisms, like the tiny plankton that live in the ocean, are composed of just one cell (**Figure** 2.5).

Other organisms have many millions of cells that make up different body tissues and organs. On the other hand, eggs are some of the biggest cells around, including chicken eggs and ostrich eggs. But most cells are tiny.

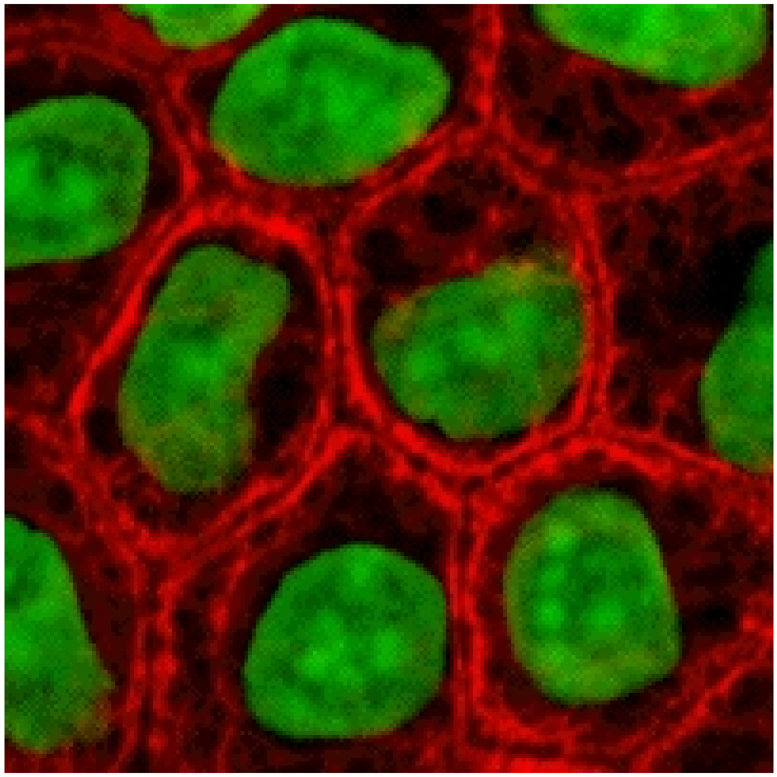

Figure 2.4: **Skin cells.** All living organisms are made of one or more cells. (18)

All cells share at least some structures. But there are thousands of kinds of cells with different structures. The cells of plants and mushrooms have a cell wall, while the cells of animals do not. The cells of most organisms have a special membrane around the DNA, but bacterial cells do not. Although the cells of different organisms are built differently, they all function much the same way. Every cell must get energy from food, be able to grow and reproduce, and respond to its environment.

Living Things Need Resources and Energy

In order to grow, reproduce, and maintain homeostasis, living things need energy. The work you do each day, from walking to writing and thinking, is fueled by energy in your cells. But where does this energy come from?

The source of energy differs for each type of living thing. In your body, the source of energy is the food you eat. All animals must eat plants or other animals in order to obtain energy and building materials. Plants themselves don't eat; they use the energy of the sun to

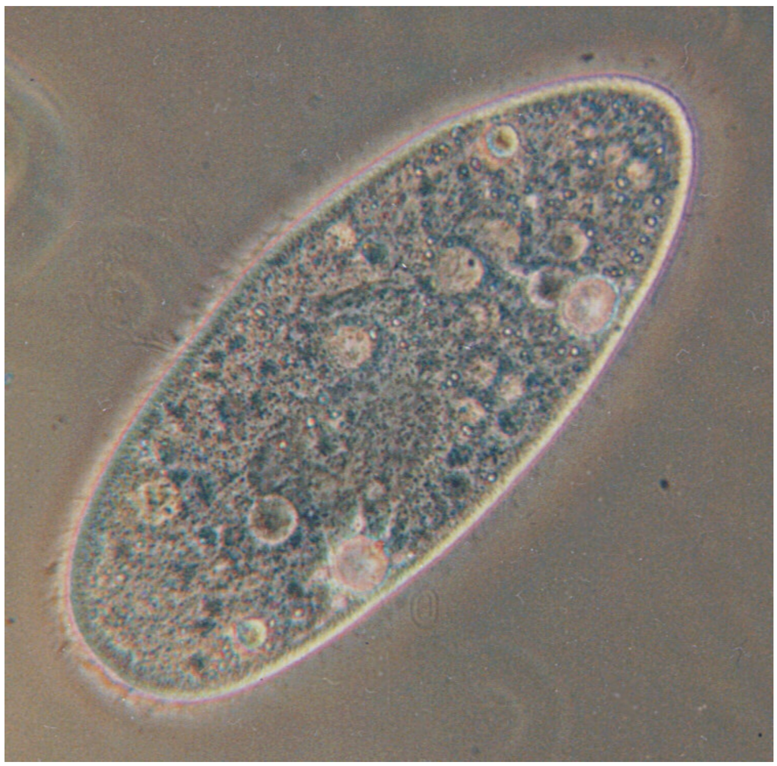

Figure 2.5: This paramecium is a one-celled organism. (9)

make their “food” through the process of photosynthesis (see *Cell Functions* chapter). Like animals, mushrooms and other fungi obtain energy from other organisms. That’s why you often see fungi growing on a fallen tree; the rotting tree is their source of energy (**Figure** 2.6). Although the means of getting energy might be different, all organisms need some source of energy. And since plants harvest energy from the sun and other organisms get their energy from plants, nearly all the energy of living things ultimately comes from the sun.

Figure 2.6: Fungi obtain energy from breaking down dead organisms, such as this rotting log. (25)

Besides obtaining energy from the foods you eat, you also need the chemical building blocks in food to build and maintain your body. For example, you get calcium for building bones from eating dairy products or leafy greens. Plants obtain nutrients from the soil. Nutrients will be discussed in the next lesson.

Lesson Summary

- All living things grow, reproduce, and maintain a stable internal environment.
- All organisms are made of cells.
- All living things need energy and resources to survive.

Review Questions

1. Define the word organism.

2. Give two examples of processes that help organisms achieve homeostasis.
3. What are three characteristics of living things?
4. What are a few ways organisms can get the energy they require?
5. What is a cell?

Further Reading / Supplemental Links

- http://publications.nigms.nih.gov/thenewgenetics/thenewgenetics.pdf
- http://en.wikipedia.org

Vocabulary

cell The smallest living unit of life; the smallest unit of structure of living organisms.

DNA Deoxyribonucleic acid; the heredity material; carries the genetic information of the cell.

heredity The passing of traits or a tendency to certain traits to the next generation through units of inheritance called genes.

homeostasis Maintaining a stable internal environment despite changes in the environment.

organism A living thing.

reproduction The process by which an organism makes a new organism with at least some of its own genes.

Points to Consider

- DNA is considered the "instructions" for the cell. What do you think this means?
- What kinds of chemicals do you think are necessary for life?
- Do you expect that the same chemicals can be in non-living and living things?

2.2 Lesson 2.2: Chemicals of Life

Lesson Objectives

- Distinguish between an element and a compound.

- Explain how elements are organized on the periodic table.
- Explain the function of enzymes.
- Name the four main classes of organic molecules that are building blocks of life.

Check Your Understanding

- What are the main properties of all living things?
- What is homeostasis?

Introduction

Physical science and biology are two different subjects in school, so you might see them as two unrelated sciences. However, understanding physical science is essential for understanding biology. Living things are subject to the same physical laws of the universe as non-living things. The rules that apply to chemical reactions in a test tube also apply to the chemical reactions that take place inside your body. To understand how living things function, we must have a little knowledge of physics and chemistry. This includes knowing what elements are and how different molecules come together to form the components of life.

The Elements

Rocks, animals, flowers, and even your body, are made up of matter. **Matter** is anything that takes up space and has mass. Matter makes up everything, living and nonliving.

Matter is composed of a mixture of elements. **Elements** are substances that cannot be broken down into simpler substances with different properties. Even chemical reactions or physical processes, like heating or crushing, cannot break it down to release a simpler substance. There are more than 100 known elements, and 92 occur naturally around us. The others have been made only in the laboratory.

Elements are made up of identical atoms. An **atom** is the simplest and smallest particle of matter that still retains the chemical properties of the element. Atoms are so tiny that only the most powerful microscopes can detect them. Atoms are the building block of all elements, and of all matter. Each element has a different type of atom, and is represented with a one or two letter symbol. For example, the symbol for oxygen is O and the symbol for carbon is C.

Atoms themselves are composed of even smaller particles, including: the positively charged **protons**, the uncharged **neutrons**, and the negatively charged **electrons**. Protons and neutrons are located in the center of the atom, or the nucleus, and the electrons move around the nucleus. How many protons and neutrons an atom has determines what element it is. For example, Helium (He) always has two protons (**Figure** 2.7), while Sodium (Na) always has 11. To restate this, all the atoms of a particular element have the exact same number of protons, and the number of protons is that element's **atomic number**.

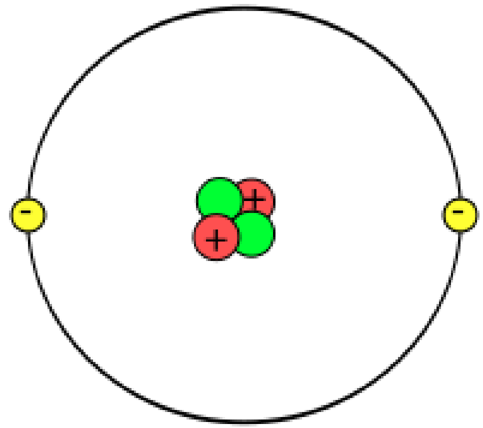

Figure 2.7: An atom of Helium (He) contains two positively charged protons (red), two uncharged neutrons (green), and two negatively charged electrons (yellow). (17)

The Periodic Table

Each element also has unique properties, such as density, boiling point, and how well it dissolves ("solubility"). **Density** is the mass of the substance per unit of volume. That means that if you take an equal volume of different elements, each different sample will weigh a different amount. For example, a liter of the metal mercury weighs 13 times as much as a liter of water. The **boiling point** is the temperature at which an element will change from a liquid to a gas. For example, the boiling point of water is 100 degrees Celsius. Once you heat water to this temperature, you see bubbles form as the water turns into vapor. Each element has a different boiling point. **Solubility** is how well a substance will dissolve in water. You can dissolve more sugar in a liter of water than salt, because sugar is more soluble than salt. Density, boiling point, and solubility have unchanging values for each element.

In 1869, Dmitri Mendeleev constructed the periodic table in 1869, organizing all the elements according to their atomic number, density, boiling point, solubility, and other values. As mentioned above, each element has a one or two letter symbol. For example, H stands for hydrogen and Au for gold. The vertical columns in the periodic table are known as groups and elements in groups tend to have very similar properties. The table is also divided into rows, known as periods.

Group 1 (see **Figure** 2.8) contains the highly reactive metals, such as sodium (Na) and lithium (Li). Just a small amount of these metals will explode into flames when put into water. Another group are the less-reactive metals, such as gold (Au) and platinum (Pt). Since they will not react readily with air and tarnish, these metals are highly valued for making jewelry. There are also highly reactive nonmetals, such as chlorine and oxygen, and some nonreactive gases, such as helium (He) and neon (N), which you might recognize from helium balloons and neon signs.

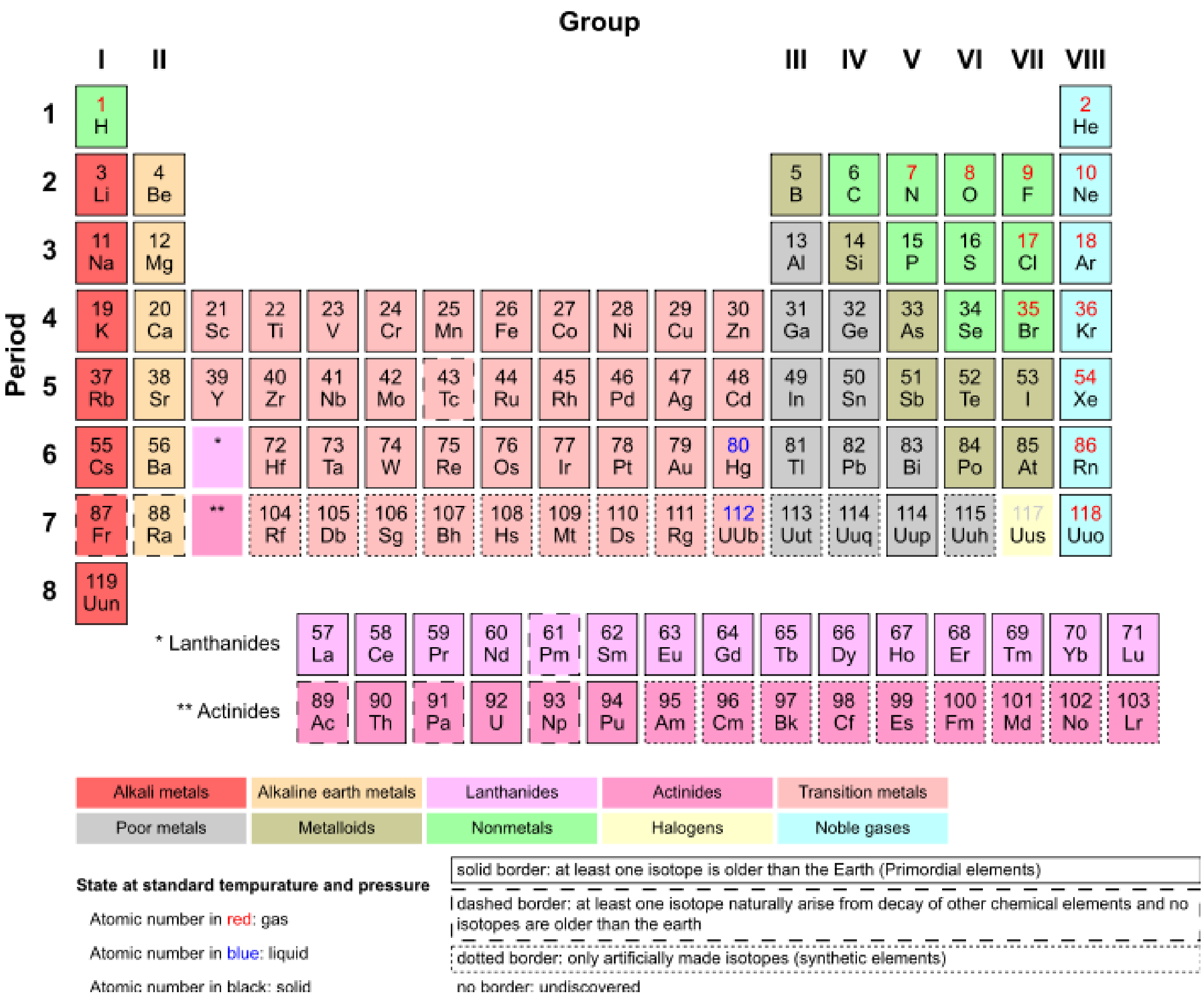

Figure 2.8: The periodic table groups the elements based on their properties. (30)

Chemical Reactions

A **molecule** is any combination of two or more atoms. The oxygen in the air we breathe is two oxygen atoms connected by a chemical bond to form O_2, or molecular oxygen. A carbon dioxide molecule is a combination of one carbon atom and two oxygen atoms. Because carbon dioxide includes two different elements it is a "compound" as well as a molecule.

A **compound** is any combination of two or more elements. A compound usually has very different properties from the elements that it contains. Elements and combinations of elements make up all the diverse types of matter in the universe.

The process by which two different elements come together to form a compound is one example of a **chemical reaction**. For example, hydrogen and oxygen together form water. Water has the properties of a liquid, not the properties of the gases hydrogen and oxygen. Water is the **product**, or end result, of the chemical reaction while hydrogen and oxygen are the **reactants**, or "ingredients" necessary for the chemical reaction.

One important chemical reaction in your everyday life is oxidation, or the combination of oxygen and another element. Examples of oxidation are burning and rusting. When oxygen combines with gas on your stove top, the reaction releases heat that you can use to cook with. (In fact, since fires need oxygen to burn, most fire extinguishers are composed of heavier gasses that will displace the oxygen, smothering the fire.) Rust is formed when oxygen combines with iron (**Figure** 2.9). These are a few examples of chemical reactions.

Figure 2.9: Rust is the result of a chemical reaction between iron and oxygen. (16)

Organic Compounds

The chemical components of living things are known as **organic compounds**, which means they contain the element carbon (C). Living things are made up of compounds that are quite large. These large compounds molecules, known as **macromolecules**, are made of smaller molecules. You might recognize some of these organic molecules as parts of the food you eat (**Figure** 2.16). Through eating food, we obtain the organic molecules we need to grow and be healthy.

Table 2.1: **The Four Main Classes of Organic Molecules**

	Proteins	Carbohydrates	Lipids	Nucleic Acids
Elements	C,H,O,N,S	C,H,O	C,H,O,P	C,H,O,P,N
Examples	Enzymes, muscle fibers, antibodies	Sugar, Starch, Glycogen, Cellulose	Phospholipids in membranes, fats, oils, waxes, steroids	DNA, RNA, ATP
Monomer (small building block molecule)	Amino acids	Sugars	Often include fatty acids	Nucleotides

Organic compounds all contain the elements carbon (C) and hydrogen (H). The chain of carbon and hydrogen in organic compounds is sometimes called the "backbone" of organic compounds since they make up the core center structure. What makes organic compounds different from one another is the **functional groups**, groups of atoms that have unique chemical properties. The addition of a functional group vastly changes the properties of the carbon-hydrogen backbone of organic compounds. Each organic compound is therefore suited to its unique role in living things.

Carbohydrates

Essentially, carbohydrates are sugars or long chains of sugars. An important role of **carbohydrates** is to store energy. Glucose is a simple sugar molecule with the chemical formula $C_6H_{12}O_6$. Sugar is one type of carbohydrate, but carbohydrates also include long chains of connected sugar molecules. These chains of sugar molecules can be used to store sugar for later use, such as in the form of starches or glycogen. Plants store sugar in long chains called *starch*, whereas animals store sugar in long chains called *glycogen*. Both storage molecules contain hundreds or thousands of linked glucose molecules. Chains of sugar molecules also can be used as structural molecules. For example, the hard skeletons of insects and lobsters are made of chitin, a type of carbohydrate. These long chains of sugar molecules are know as **polysaccharides**. You get the carbohydrates you need for energy from eating carbohydrate-rich foods, including fruits and vegetables, as well as grains such as bread, rice, or corn.

The chemical formula $C_6H_{12}O_6$ of glucose means that this molecule has 24 atoms: 6 carbon atoms, 12 hydrogen atoms, and 6 oxygen atoms. Carbohydrates have a general chemical formula consisting of twice as many hydrogen atoms as carbon and oxygen atoms. Glucose is a **monomer**, a single unit that when linked together with other monomers forms a long chain known as a polymer. Starch is an example of a polymer.

Proteins

Proteins have many different functions in living things. Enzymes are a type of protein. **Antibodies** that protect your body from disease are proteins, and your muscles are made of protein. All proteins are made of monomers (small building block molecules) called amino acids that line up to form long chains. There are only 20 common amino acids. These amino acids have the general chemical formula $H_2NCHRCOOH$, where R is a "side group" which varies between amino acids. It is this side group that gives the amino acids its physical and chemical properties. These amino acids form in thousands of different combinations, generating up to 100,000 unique proteins. Proteins can differ in both the number and order of amino acids. Small proteins have just a few hundred amino acids, whereas the largest proteins have over 25,000 amino acids.

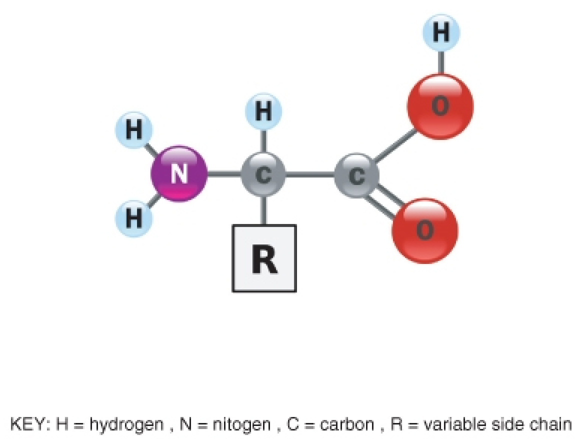

Figure 2.10: General Structure of Amino Acids. This model shows the general structure of all amino acids. Only the side chain, R, varies from one amino acid to another. For example, in the amino acid glycine, the side chain is simply hydrogen (H). In glutamic acid, in contrast, the side chain is CH_2CH_2COOH. 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 (29)

After a cell makes a protein chain, the chain folds into a 3-dimensional structure (**Figure** 2.11). Proteins fold based on the sequence and properties of the amino acids. The properties of amino acids can vary widely, so the position of each amino acid in a protein is important. Each folded protein has its own unique shape. It is this shape that gives the protein its function. The primary structure of a protein is the linear sequence of amino acids. The amino acids appear as "beads on a string," as shown in the figure below. The folding of the protein into the 3-dimensional working molecule is based on the initial primary sequence of amino acids.

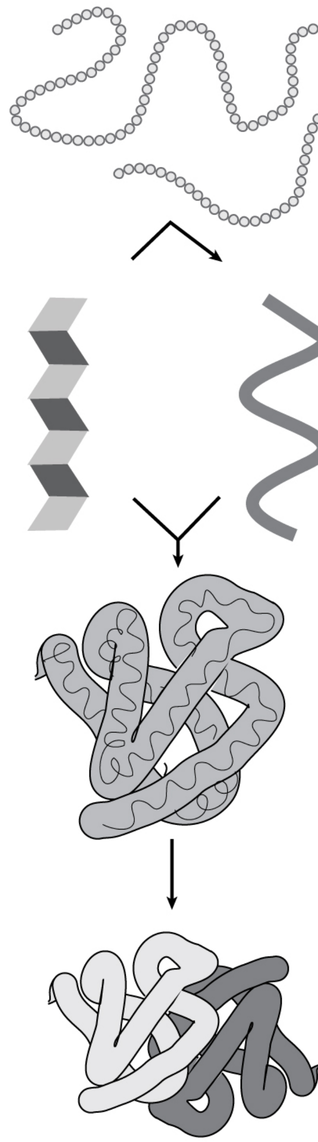

Figure 2.11: Proteins fold into unique 3-dimensional structures, starting with the linear "beads on a string," shown at the top, to the complex structure on the bottom. (14)

It's important for you and other animals to eat food with protein because we cannot synthesize some of these amino acids ourselves. You can get proteins both from plant sources such as beans and from animal sources, like milk or meat. When you eat food with protein, your body breaks the proteins down into individual amino acids and uses them to build new proteins. Therefore, you really are what you eat!

Lipids

The lipids - the fats, oils, and waxes - are a diverse group of organic compounds. **Lipids** are not soluble in water. (As you probably know, oil and water don't mix.) The most common lipids in your diet are probably fats and oils. Fats are solid at room temperature, whereas oils are fluid. Animals use fats for long-term energy storage and insulation. Plants use oils for long-term energy storage. When preparing food, we often use animal fats, such as lard and butter, or plant oils, such as olive oil or canola oil.

There are many more type of lipids that are important to life. One of the most important are the **phospholipids** (see the chapter titled *Cell Functions*) that make up the membranes that surround all cells. **Steroids** are the basis for the hormones like testosterone and estrogen. **Waxes** are useful lipids for plants and animals since they are waterproof. Plants coat their leaves in a waxy covering to prevent water loss, while bees use wax to make their honeycombs.

Nucleic acids

Nucleic acids are long chains of **nucleotides**, which are units composed of a sugar, a nitrogen-containing base, and a phosphate group. Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are the two main nucleic acids. DNA is the molecule that stores our genetic information and RNA is involved in making proteins. Nucleotides also make up the high-energy molecule Adenosine Triphosphate (**ATP**). ATP is the energy currency of the cell. Every time you think a thought or move a muscle, you are using the energy stored in ATP.

The following series of **Figures** 2.12, 2.13, 2.14 and 2.15 show examples.

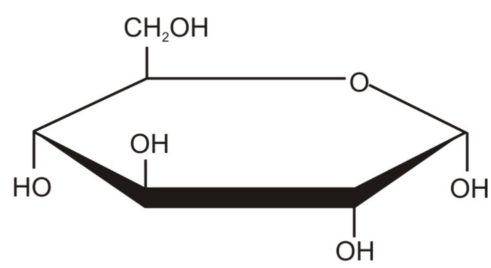

Figure 2.12: (A) A molecule of glucose (a carbohydrate). (4)

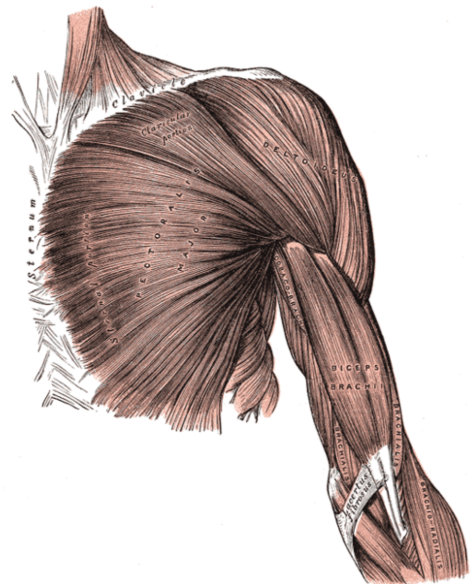

Figure 2.13: (B) Muscle fibers (protein). (31)

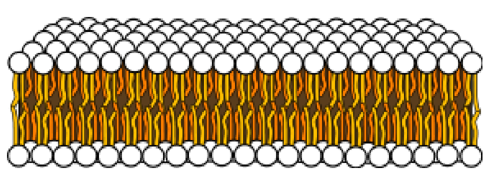

Figure 2.14: (C) Phospholipids in a membrane (lipid). (12)

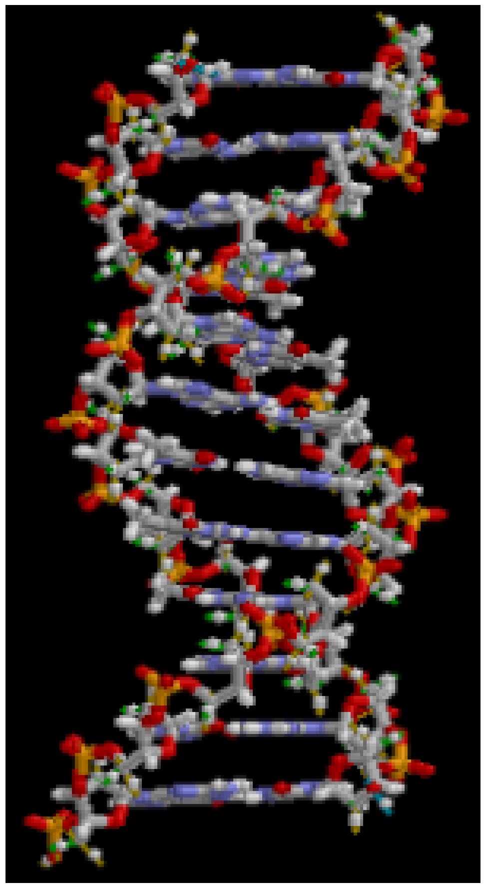

Figure 2.15: (D) DNA (nucleic acid). (3)

The

Figure 2.16: A healthy diet includes protein, fat, and carbohydrate. (27)

Enzyme Reactions

The oxidation reaction occurs readily, but not all reactions move so quickly. Others can take quite a while. Since many of the body's necessary chemical reactions would take years to happen on their own, you need the help of enzymes. **Enzymes** speed up chemical reactions, often by bringing the reactants closer together so they can interact more easily (**Figure** 2.17). Enzymes attach to, or **bind**, specifically to the reactants. Because enzymes are so specific, you have a different enzyme for every chemical reaction in your body. A single cell may contain hundreds or thousands of different enzymes.

When an enzymes attaches, or binds, to another molecule, that molecule is referred to as the **substrate**. The enzyme is usually much bigger than the substrate.

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** 2.18. The biochemical reaction shown in the figure requires about three times as much 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.

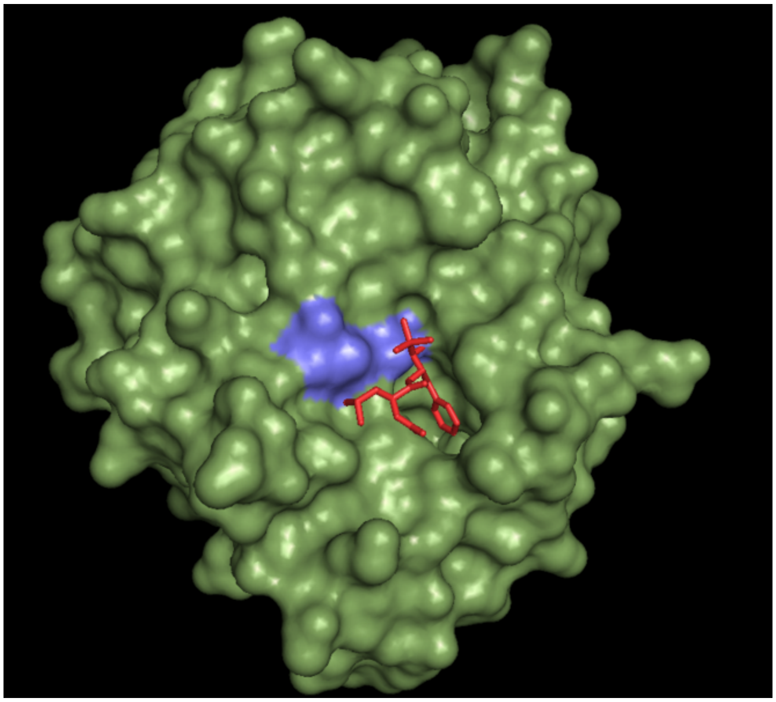

Figure 2.17: The enzyme (green) binds to the substrate (red) to speed up a chemical reaction. (26)

As discussed above, enzymes 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** 2.19).
- By binding reactants at the active site, enzymes also position reactants correctly, so they do not have to overcome the forces that would otherwise push them apart. This allows the molecules to interact with less 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*

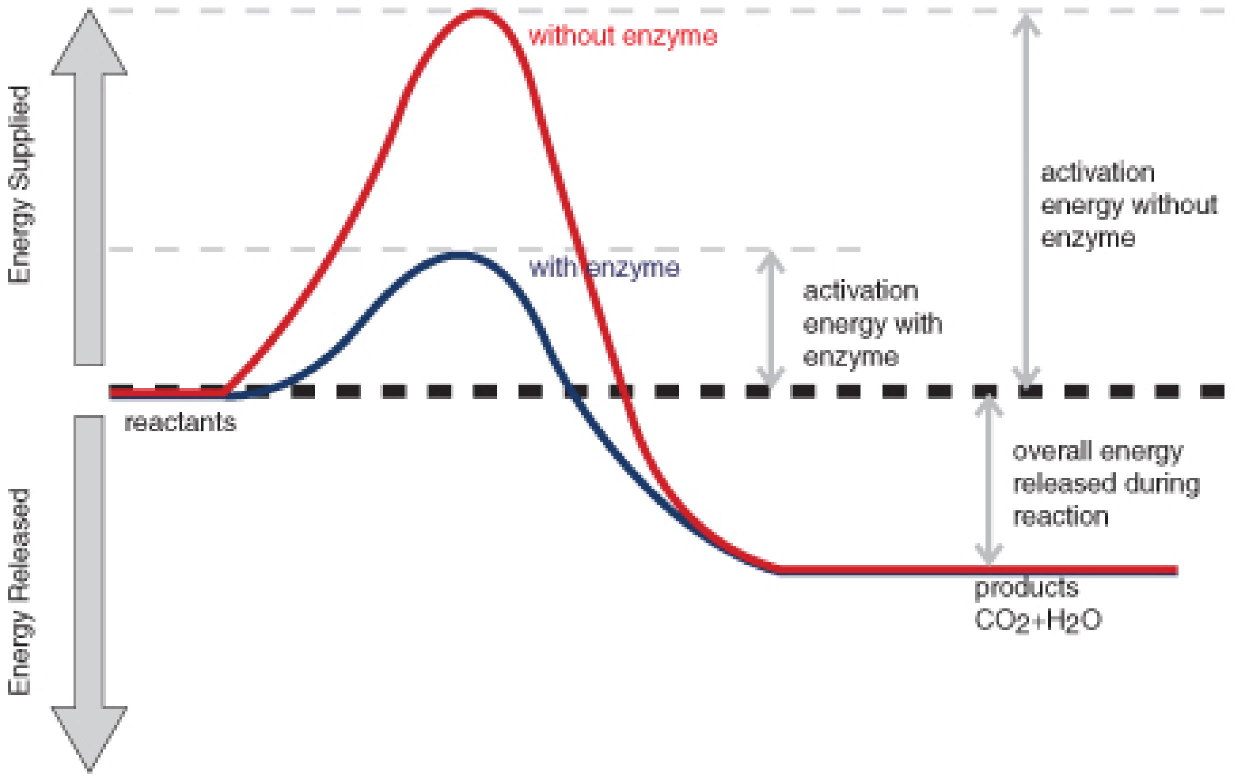

Figure 2.18: The reaction represented by this graph involves the reactants glucose ($C_6H_{12}O_6$) and oxygen (O_2). The products of the reaction are carbon dioxide (CO_2) and water (H_2O). Energy is also released during the reaction. The enzyme speeds up the reaction by lowering the activation energy needed for the reaction to start. Compare the activation energy with and without the enzyme. (24)

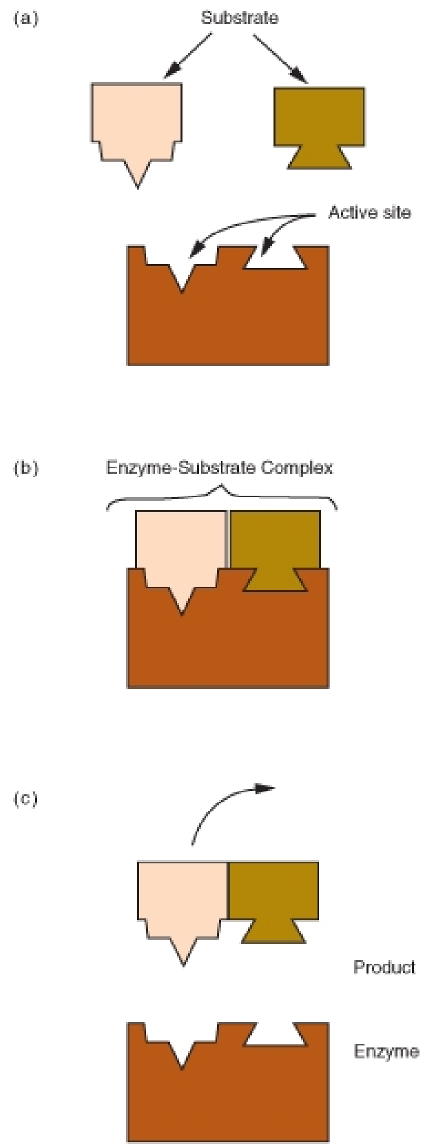

Figure 2.19: This enzyme molecule binds reactant molecules—called substrate—at its active site, forming an enzyme-substrate complex. This brings the reactants together and positions them correctly so the reaction can occur. After the reaction, the products are released from the enzyme's active site. This frees up the enzyme so it can catalyze additional reactions. (11)

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 ˚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.

Lesson Summary

- Elements are substances that cannot be broken down into simpler substances with different properties.
- Elements have been organized by their properties to form the periodic table.
- Two or more atoms can combine to form a molecule.
- Molecules consisting of more than one element are called compounds.
- Reactants can combine through chemical reactions to form products.
- Enzymes can speed up a chemical reaction.
- Living things are made of just four classes of macromolecules: proteins, carbohydrates, lipids, and nucleic acids.

Review Questions

1. What is density?
2. What are the 4 main classes of organic compounds?
3. Would water, with the symbol H_2O, be considered an element or a compound?
4. How many types of atoms make up gold?
5. Why do you need fats in your diet?
6. Sugar is what kind of organic compound?
7. What is an atom?
8. What monomers make up proteins?
9. Name a few examples of proteins.
10. Name a few examples of lipids in organisms.
11. What are two nucleic acids?

Further Reading / Supplemental Links

- http://ghr.nlm.nih.gov/handbook/howgeneswork/protein
- http://ghr.nlm.nih.gov/handbook/basics/dna

- http://publications.nigms.nih.gov/thenewgenetics/chapter1.html

Vocabulary

amino acids Monomers that combine to make protein chains.

atom The simplest and smallest particle of matter that still retains the physical and chemical properties of the element; the building block of all matter.

ATP Adenosine triphosphate, the energy ”currency” of the cell.

carbohydrates Class of organic compound that includes sugar, starch, cellulose and chitin.

electron A negatively charged particle in the atom, found outside of the nucleus.

element A substance that cannot break down into a simpler substance with different properties.

enzyme Protein that speeds up a chemical reaction by binding to the reactants (substrates).

functional groups Groups of atoms that give a compound its unique chemical properties.

lipids Class of organic compound that includes fats, oils, waxes and phospholipids.

matter Anything that takes up space and has mass.

neutrons The non-charged particle of the atom; located in nucleus of the atom.

nucleic acid Class of organic compound that includes DNA and RNA.

organic compounds Compounds made up of a carbon backbone and associated with living things.

phospholipids Lipid molecule that makes up cell membranes.

product The end result formed from a chemical reaction.

protein Class of organic compound consisting of a chain of amino acids; includes enzymes and antibodies.

Proton The positively charged particle of the atom; located in nucleus of the atom.

Reactants The raw ingredients in a chemical reaction.

Waxes A water-proof lipid.

Points to Consider

- Do you expect the genetic information in the DNA of a cow to be the same or different from that in a crow?
- If we are all composed of the same chemicals, how do all organisms look so different?
- What characteristics would you use to distinguish and classify living things?

2.3 Lesson 2.3: Classification of Living Things

Lesson Objectives

- Explain what makes up a scientific name.
- Explain what defines a species.
- List the information scientists use to classify organisms.
- List the three domains of life and the chief characteristics of each.

Check Your Understanding

- What are the basic characteristics of life?
- What are the four main classes of organic molecules that are building blocks of life?

Introduction

When you see an organism that you've never seen before, you probably automatically classify it into a specific group. If it's green and leafy, you would probably call it a plant. If it's long and slithers, you would probably classify it as a snake. How do you make such assignments? You look at the physical features of the organism and think about what it has in common with other organisms. Scientists do the same thing when they classify living things. But scientists classify organisms not only by their physical features, but also by their evolutionary history and relatedness. Lions and tigers look like each other more than they look like bears. But it's not just appearance. The two cats are actually more closely related to each other than to bears. How related organisms are is an important basis for classifying them.

Classifying Organisms

People have been concerned with classifying organisms back to the time of the Greeks and Romans. The Greek philosopher Aristotle developed a classification system that divided living things into several groups that we still use today, including mammals, insects, and reptiles. Carl Linnaeus (1707-1778) (**Figure** 2.20) built on Aristotle's work to produce his own extensive classification system and invented the way we name organisms by their genus and species. For example, a coyote's species name is *Canis latrans*. "Latrans" is the **species** and "canis" is the **genus**, a larger group that includes dogs, wolves, and other dog-like animals. Linnaeus is considered the inventor of modern **taxonomy,** the science of naming and grouping organisms. He was especially interested in plants, and he used differences in flowers to classify each plant into groups. Modern taxonomists have reordered many groups of organisms since Linnaeus. The main categories biologists use are listed here from the most specific to the broadest category (**Figure** 2.21). In other words, there are many species in each genus, many genera (plural for "genus") in each family, and so on. The broadest and most inclusive category is the domain. It is currently believed that there are three domains and six kingdoms. We will discuss these groups more later.

But how do taxonomists decide what domain or family an organism belongs to? Like Linnaeus, they still look at the physical features of the organisms and group organisms that look similar together (**Figure** 2.22). But taxonomists also try to piece together evolutionary relationships when assigning organisms to a specific group. By looking at **fossils,** ancient remains of living things, they can tell if organisms share a recent common ancestor–sort of like a "grandparent" species. A common ancestor is an ancestor shared by two groups of organisms. For example lions and tigers share a common ancestor; both species are descended from an ancient cat. If two species share a recent common ancestor, it means they are closely related and they will be placed in the same group.

Another way to determine evolutionary relationships is by looking for similarities or differences in organisms' **DNA**. The number of differences in two organisms' DNA can show how closely related the two organisms are. You might expect, for example, that human DNA is more similar to chimpanzee DNA than to bacterial DNA. (And it is.) How biologists determine evolutionary history will be discussed in more detail in the *Evolution* chapter.

Naming Organisms

Carl Linnaeus recognized a need for a system of names for each species. If we just used common names, we would have many different names in many different languages for the

Figure 2.20: In the 18th century, Carl Linnaeus invented the two-name system of naming organisms (genus and species) and introduced the most complete classification system then known. (8)

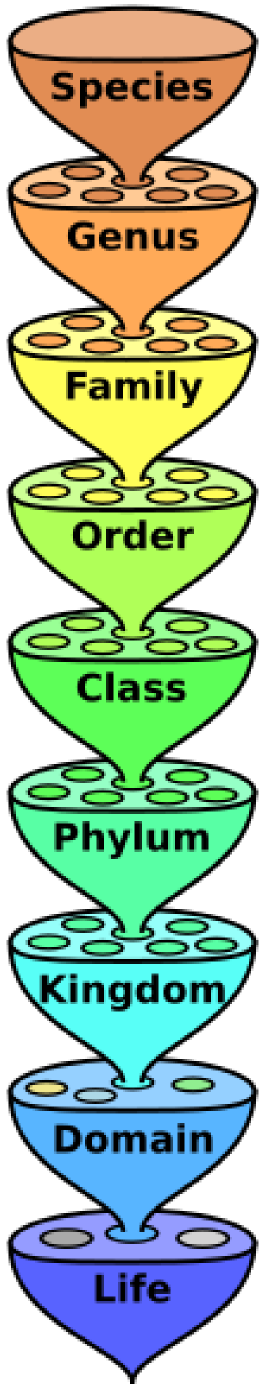

Figure 2.21: This diagram illustrates the classification categories for organisms, with the broadest category (Life) at the bottom, and the most specific category (Species) at the top. (10)

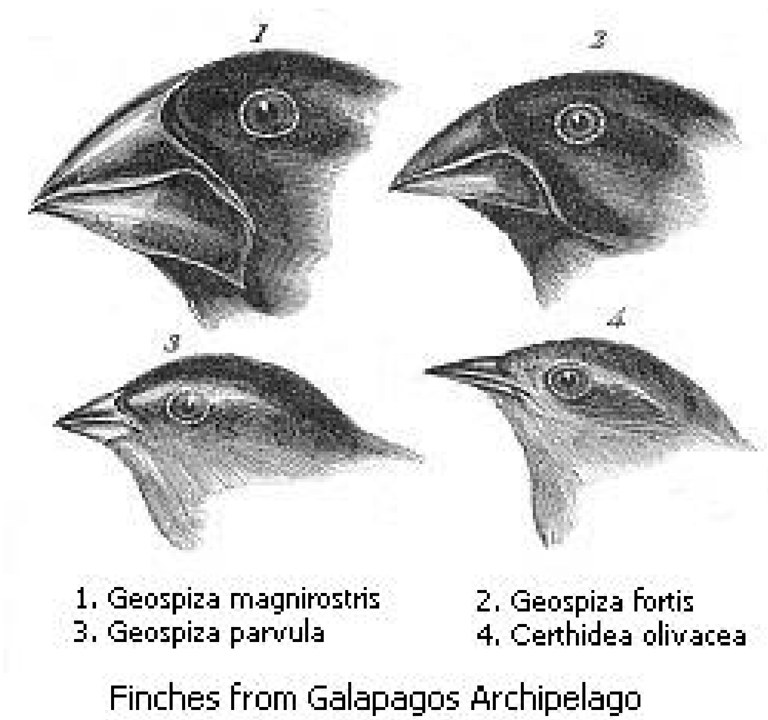

Figure 2.22: Darwin suggested that these Galapagos Island finches share a common ancestor and evolved different beaks because they were eating different foods. Modern research confirms this hypothesis. (23)

same species. To solve this problem, Linnaeus developed **binomial nomenclature,** a way to give a scientific name to every organism. Each species receives a two-part name in which the first word is the genus (a group of species) and the second word refers to one species in that genus. For example, the red maple, *Acer rubra,* and the sugar maple, *Acer saccharum,* are both in the same genus (**Figures** 2.23, 2.24 and 2.25). Notice that the genus is capitalized and the species is not, and that the whole scientific name is in italics. The names are nearly always in Latin, the universal language of scholars throughout European history. Sometimes, biologists use Greek or other words. For example, *Microtus pennsylvanicus* is a species of mouse in Pennsylvania and nearby states.

Figure 2.23: (5)

Figure 2.24: (7)

Even though naming species is straightforward, deciding if two organisms are the same species can sometimes be difficult. Linnaeus defined each species by the distinctive physical characteristics shared by these organisms. But two members of the same species may look quite different. For example, people from different parts of the world sometimes look very different, but we are all the same species (**Figure** 2.26).

So how is a species defined? A **species** is group of individuals that can interbreed with one another and produce fertile offspring; a species does not interbreed with other groups. By this definition, two species of animals or plants that do not interbreed are not the same

Figure 2.25: These leaves in the top and middle photographs are from two different species trees in the Acer, or maple, genus. One of the characteristics of the maple genus is winged seeds (bottom). (28)

species. For example, tigers and lions can mate in zoos and produce kittens that are half tiger and half lion. But we still consider tigers and lions separate species. The two cats look and behave differently and are not known to interbreed in the wild, even though they can. Groups of lions and tigers do not interbreed.

Domains of Life

All life can be divided into 3 domains: Bacteria, Archaea, and Eukarya (**Figures** 2.27, 2.28 and 2.29). This is the largest and least specific classification, so the organisms might not look much alike, but they do have some very important traits in common. For example, you might be surprised that mushrooms, plants, and people are all in the same domain. But when you look at the cells of mushrooms, plants, and people, you will see that they do have some similar features. They are all eukaryotic organisms, or in the domain Eukarya. The other two domains are composed of prokaryotic organisms. Prokaryotic and eukaryotic cells will be discussed in the chapter titled *Cells and Their Functions*.

All the cells in the domain **Eukarya** keep their DNA inside a membrane, a structure called the nucleus. The cells of other domains have DNA, but it is not inside a nucleus. The domain Eukarya is made up of four diverse kingdoms: plants, fungi, animals, and protists.

Plants, such as trees and grasses, survive by capturing energy from the sun, a process called photosynthesis. Animals survive by eating other organisms or the remains of other organisms. Animals range from tiny worms to insects, dogs, and the largest dinosaurs and whales. Fungi, such as mushrooms and molds, also survive by eating other organisms or the remains of other organisms. The last group listed here are the **protists**. Protists are not all descended from a single common ancestor in the way that plants, animals, and fungi are. Protists are a sort of miscellaneous group; they are all the organisms that are not something else. Protists are a diverse group of organisms that include many kinds of microscopic one-celled organisms,

Figure 2.26: These children are all members of the same species, *Homo sapiens*. (15)

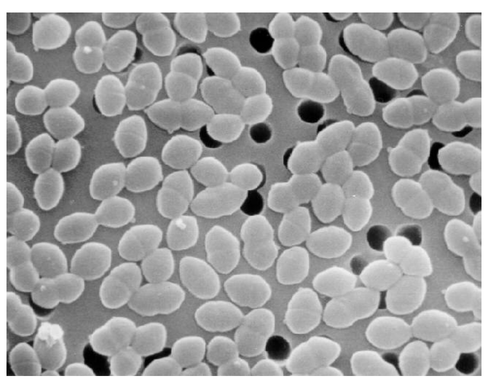

Figure 2.27: The "Group D" Streptococcus organism is in the domain *Bacteria*, one of the three domains of life. (2)

Figure 2.28: The Halobacterium is in the domain *Archaea*, one of the three domains of life. (1)

Figure 2.29: The Western Gray Squirrel is in the domain *Eukarya*, one of the three domains of life. (19)

such as algae and plankton, but also giant seaweeds that can grow to be 200 feet long (an alga protist is shown in **Figure** 2.30). Plants, animals, fungi, and protists might seem very different, but remember that if you look through a microscope, you would find cells with a membrane-bound nucleus in all them.

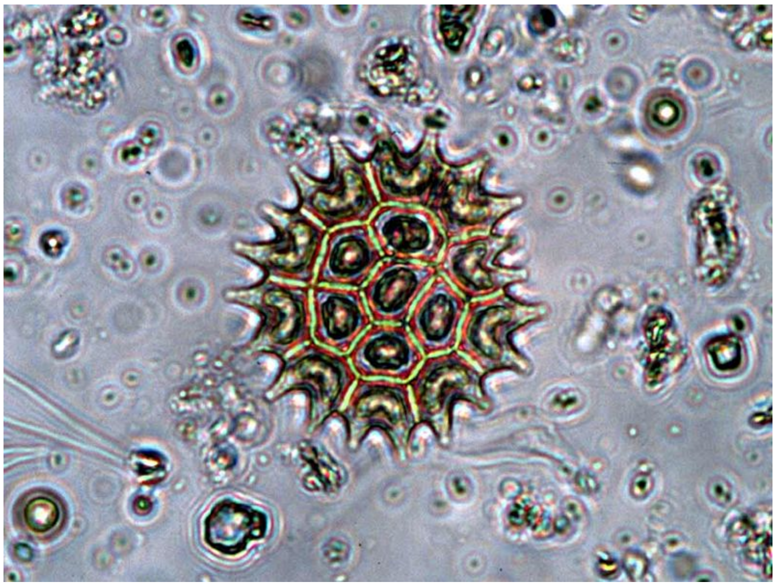

Figure 2.30: This microscopic alga is a protist in the domain Eukarya. (21)

The cells of the two other domains - the **Archaea** and the **Bacteria** - do not have a nucleus. All the cells in both domains are tiny, microscopic one-celled organisms that can reproduce without sex by dividing in two. The difference between the archaea and the bacteria is in their cell walls. Also, archaea often live in extreme environments like hot springs, geysers, and salt flats, while bacteria are abundant and live almost everywhere. A teaspoon of soil can contain 100 million to a billion individual bacteria. Bacteria obtain energy in lots of different ways. Some infect plants and animals and cause disease. Others break down dead organisms. The **cyanobacteria** photosynthesize, like plants. In fact, the ancestors of today's cyanobacteria invented photosynthesis more than two billion years ago.

Table 2.2: **Three domains of life: Bacteria, Archaea, and Eukarya**

	Archaea	Bacteria	Eukarya
Multicelluar	No	No	Yes
Cell Wall	Yes, without peptidoglycan	Yes, with peptidoglycan	Varies. Plants and fungi have a cell wall; animals do not.
Nucleus (DNA inside a membrane)	No	No	Yes

Table 2.2: (continued)

	Archaea	Bacteria	Eukarya
Organelles inside a membrane	No	No	Yes

Viruses

We have all heard of viruses. The flu and many other diseases are caused by viruses. But what is a virus? Based on the material presented in this chapter, are viruses living? No.

A virus is essentially nucleic acid surrounded by protein (**Figure** 2.31). It is not made of a cell; it does not metabolize, it does not maintain homeostasis. Viruses need to infect a host cell to reproduce; they cannot reproduce on their own. However, viruses do evolve. So a virus is very different than any of the organisms that fall into the three domains of life.

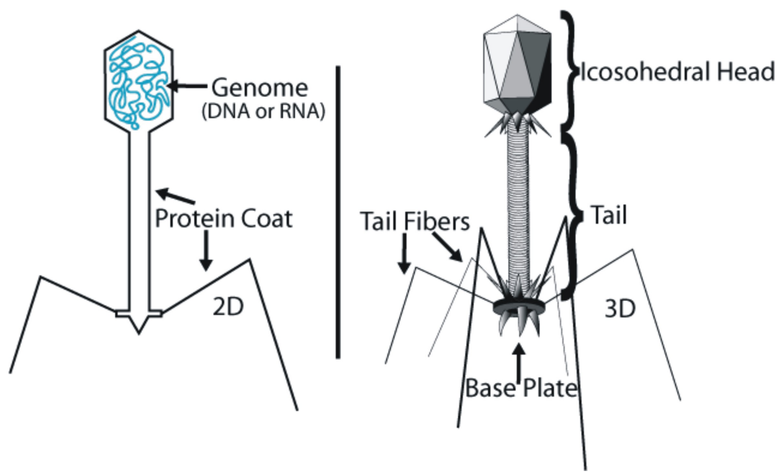

Figure 2.31: These "moon lander" shaped complex virus infects *Escherichia coli* bacteria. (20)

Lesson Summary

- Scientists have defined several major categories for classifying organisms: domain, kingdom, phylum, class, order, family, genus, and species.
- The scientific name of an organism consists of its genus and species.
- Scientists classify organisms according to their evolutionary histories and how related they are to one another - by looking at their physical features, the fossil record, and DNA sequences.
- All life can be classified into three domains: Bacteria, Archaea, and Eukarya.

Review Questions

1. Who designed modern classification and invented the two-part species name?
2. In what domain are humans?
3. *Quercus rubra* is the scientific name for the red oak tree. What is the red oak's genus?
4. In what domain are mushrooms?
5. Is it possible for organisms in two different classes to be in the same genus?
6. How are organisms given a scientific name?
7. Define a species.
8. What kingdoms make up the domain Eukarya?
9. What is the name for the scientific study of naming and classifying organisms?
10. What information do scientists use to classify organisms?
11. If molecular data suggests that two organisms have very similar DNA, what does that say about their evolutionary relatedness?
12. Can two different species ever share the same scientific name?
13. If two organisms are in the same genus, would you expect them to look much alike?

Further Reading / Supplemental Links

- http://www.ucmp.berkeley.edu/history/linnaeus.html
- http://www.physicalgeography.net/fundamentals/9b.html
- http://www.pbs.org/wgbh/nova/orchid/classifying.html

Vocabulary

archaea Microscopic one-celled organisms with no nucleus that tend to live in extreme environments.

bacteria Microscopic one-celled organisms with no nucleus that live everywhere.

binomial nomenclature The system for naming species in which the first word is the genus and the second word is the species.

cyanobacteria Photosynthetic bacteria.

DNA Deoxyribonucleic acid; Nucleic acid molecule that stores the genetic information.

Eukarya Domain in which cells have a nucleus that includes plants, animals, fungi, and protists.

fossils Ancient remains of living things; includes bone, teeth, and impressions.

nucleus Tiny structure inside of some cells that walls off the DNA from the rest of the cell; DNA wrapped inside a membrane.

species Group of organisms that can mate with one another to produce fertile offspring but do not mate with other such groups.

taxonomy The science of naming and classifying organisms.

Points to Consider

- This lesson introduced the diversity of life on Earth. Do you think it is possible for cells from different organisms to be similar even though the organisms look different?
- Do you think human cells are different from bacterial cells?
- Do you think it is possible for a single cell to be a living organism?

Image Sources

(1) CDC. *Archaea*. Public Domain.

(2) Centers for Disease Control and Prevention, United States Department of Health and Human Services. *Bacteria*. Public Domain.

(3) *DNA (nucleic acid)*. Public Domain.

(4) *a molecule of glucose (a carbohydrate)*. Public Domain.

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Chapter 3

Cells and Their Structures

3.1 Lesson 3.1: Introduction to Cells

Lesson Objectives

- Explain how cells are observed.
- Recall the cell theory.
- Explain the levels of organization in an organism.

Check Your Understanding

- What are the main characteristics of living things?
- Name the four main classes of organic molecules that are building blocks of life.

Introduction

How do lipids, carbohydrates, proteins, and nucleic acids come together to form a living organism? By forming a cell. These organic compounds are the raw materials needed for life, and a **cell** is the smallest unit of an organism that is still considered living. Cells are the basic units that make up every type of organism. Some organisms, like bacteria, consist of only one cell. Other organisms, like humans, consist of trillions of specialized cells working together. Even if organisms look very different from each other, if you look close enough you'll see that their cells have much in common. (Use of a microscope in **Figure** 3.1 helps to illustrate this.)

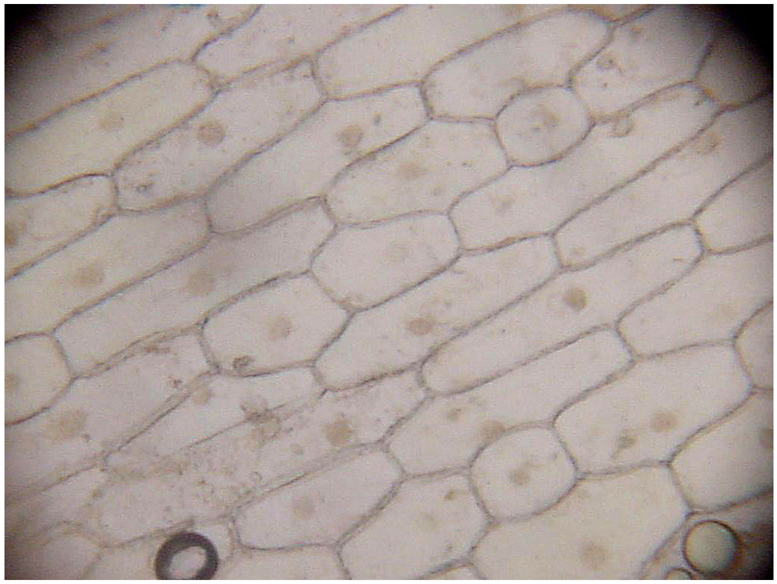

Figure 3.1: The outline of onion cells are visible under a light microscope. (9)

Observing Cells

Most cells are so tiny that you can't see them without the help of a microscope. The microscopes that students typically use at school are light microscopes. Robert Hooke created a primitive light microscope in 1665 and observed cells for the very first time. Although the light microscope opened our eyes to the existence of cells, they are not useful for looking at the tiniest components of cells. Many structures in the cell are too small to see with a light microscope.

When scientists developed more powerful microscopes in the 1950s, the field of cell biology grew rapidly. A light microscope passes a light beam through a specimen, but the more powerful **electron microscope** passes a beam of electrons through the specimen, allowing a much closer look at the cell (**Figure** 3.2).

Transmission electron microscopes (TEM), which pass an electron beam through something, are used to look at a very thin section of an organism and allow us to study the internal structure of cells. **Scanning electron microscopes** (SEM), which pass a beam of electrons across the surface of something, show the details of the shapes of surfaces, giving a 3D image.

Electron microscopes showed many small structures in the cell that had been previously invisible with light microscopes. One drawback to using an electron microscope is that it only images dead cells. A light microscope can be used to study living cells.

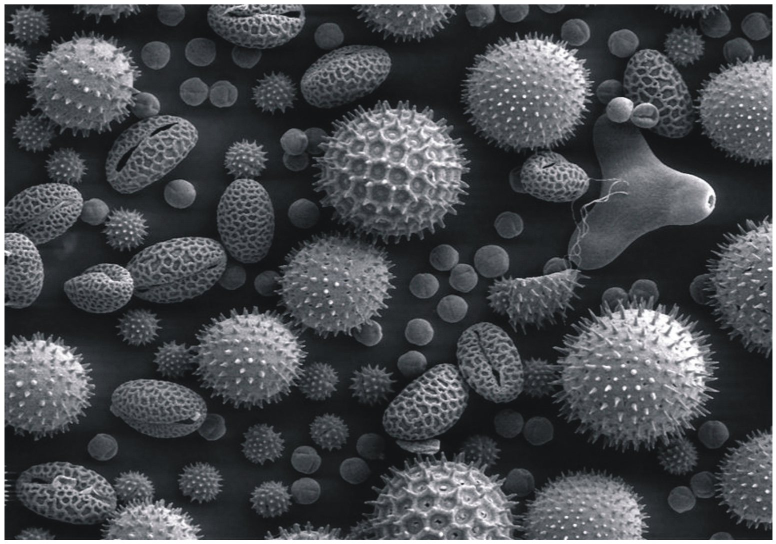

Figure 3.2: An electron microscope allows scientists to see much more detail than a light microscope, as with this sample of pollen. But a light microscope allows scientists to study living cells. (8)

Cell Theory

In 1858, after microscopes had become much more sophisticated than Hooke's first microscope, Rudolf Virchow proposed that cells only came from other cells. For example, bacteria are composed of only one cell (**Figure** 3.3) and divide in half to replicate themselves. In the same way, your body makes new cells by the division of cells you already have. In all cases, cells only come from pre-existing cells.

This concept is central to the cell theory. **The cell theory** states that:

1. All organisms are composed of cells.
2. Cells are alive and the basic living units of organization in all organisms.
3. All cells come from other cells.

As with other scientific theories, the cell theory has been supported by thousands of experiments. And, since Virchow introduced the cell theory, no evidence has ever contradicted it.

Levels of Organization

Although cells share many of the same features and structures, as we will discuss in the next section, they also can be quite different. Each cell in your body is specialized for a specific task. For example:

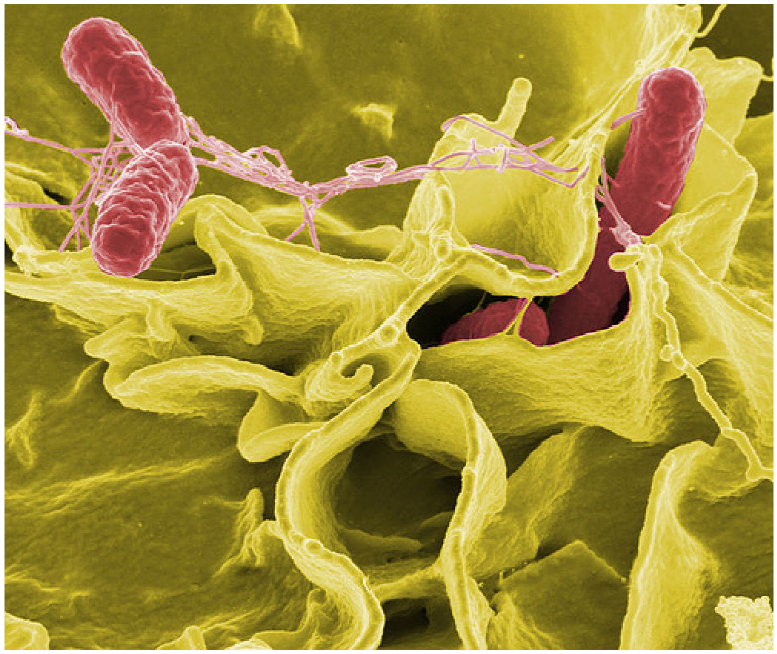

Figure 3.3: Bacteria (pink) are an example of an organism consisting of only one cell. (4)

- Red blood cells (**Figure** 3.4) are shaped with a pocket to increase their surface area for absorbing and releasing oxygen .
- Nerve cells, which can quickly transmit the sensation of touching a hot stove to your brain, are elongated and stringy to allow them to form a complex network with other nerve cells (**Figure** 3.5) .
- Skin cells (**Figure** 3.6) are flat and fit tightly together.

As you can see, cells are shaped in ways that help them do their jobs. Multicellular (many-celled) organisms have many types of specialized cells in their bodies.

While cells are the basic units of an organism, groups of specialized cells can be organized into tissues. For example, your liver cells are organized into liver tissue, which is organized into an organ, your liver. Organs are formed from two or more specialized tissues working together for a common function. All organs, from your heart to your liver, are made up of an organized group of tissues.

These organs are part of a larger organization pattern, the organ systems. For example, your brain works together with your spinal cord and other nerves to form the nervous system. This organ system must be organized with other organ systems, such as the circulatory system and the digestive system, for your body to work. Organ systems are coordinated together to form the complete organism. As you can see (**Figure** 3.7), there are many levels of organization in living things.

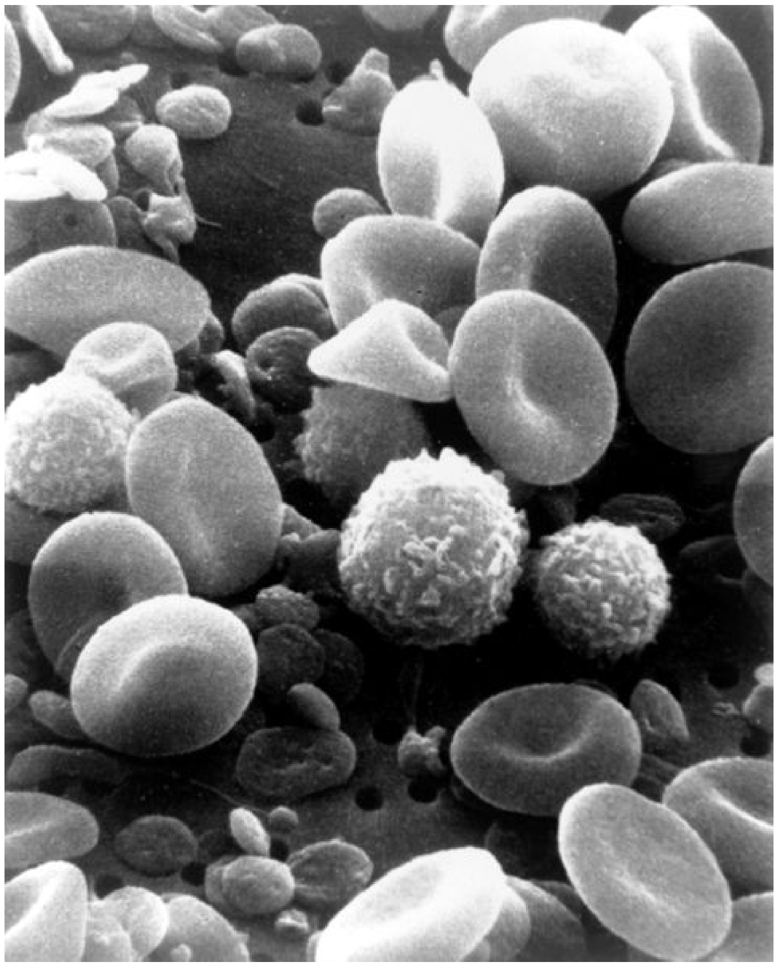

Figure 3.4: Red Blood cells are specialized to carry oxygen in the blood. (12)

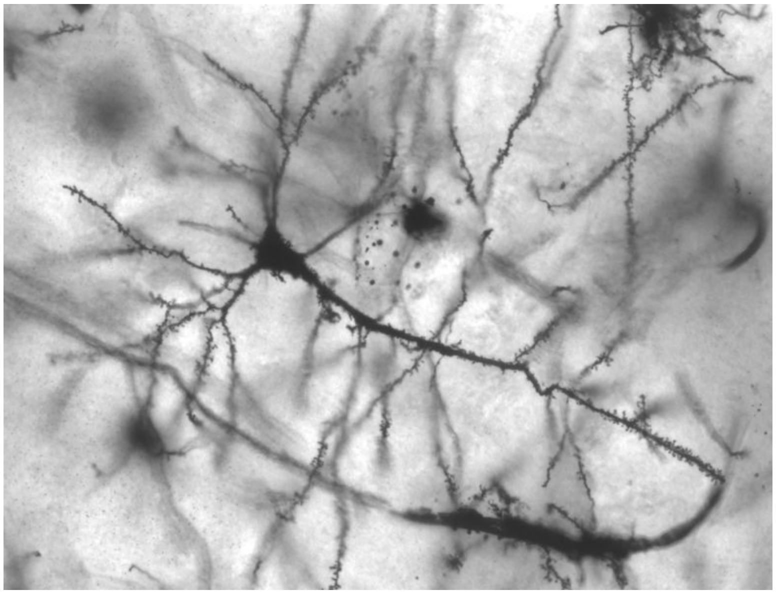

Figure 3.5: Neurons are shaped to conduct electrical impulses to many other nerve cells. (2)

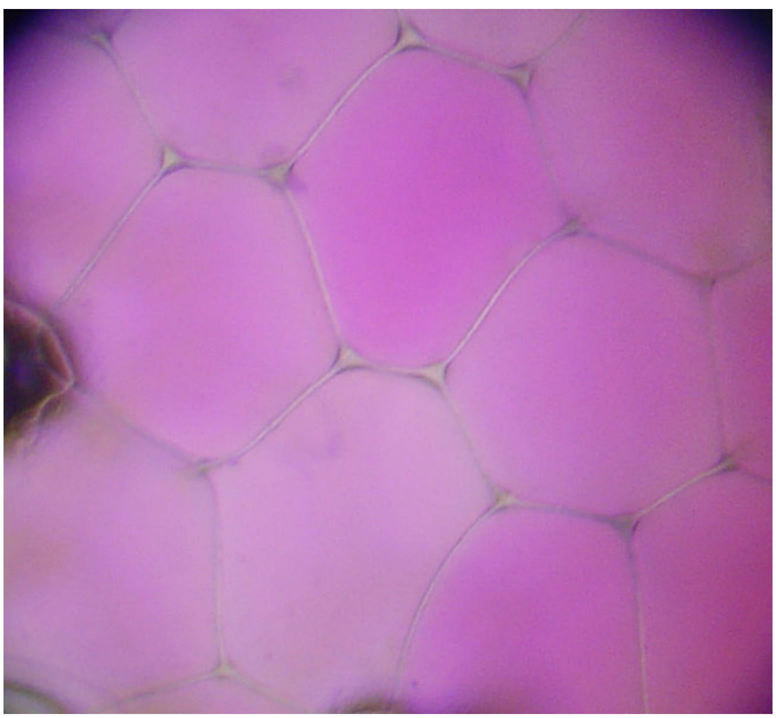

Figure 3.6: These epidermal cells make up the "skin" of plants. Note how the cells fit tightly together. (1)

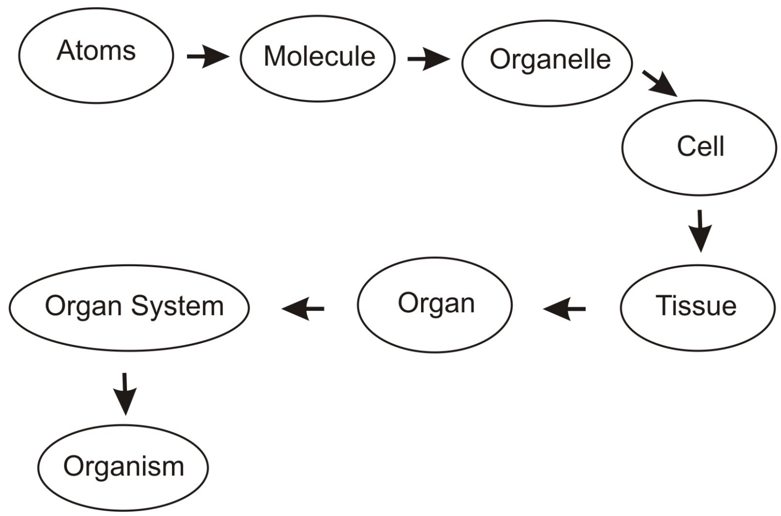

Figure 3.7: Levels of Organization, from the atom to the organism. (3)

Lesson Summary

- Cells were first observed under the light microscope, but today electron microscopes allow scientists to take a closer look at the internal structures of cells
- The Cell Theory says that
  - all organisms are composed of cells;
  - cells are alive and the basic living units of organization in all organisms; and
  - All cells come from other cells.
- Cells are organized into tissues, which are organized into organs, which are organized into organ systems, which are organized to create the whole organism.

Review Questions

1. What type of microscope would you use to study living algae cells?
2. What type of microscope would you use to study the details on the surface of a cell?
3. What type of microscope would be best for studying internal structures of cells?
4. According to the cell theory, can we synthesize a cell in the laboratory from organic molecules?
5. Do all cells work exactly the same?
6. Put the following in the correct order from simplest to most complex: organ, cell, tissue, organ system.

Further Reading / Supplemental Links

- Baeuerle, Patrick A. and Landa, Norbert. *The Cell Works: Microexplorers.* Barron's; 1997, Hauppauge, New York.
- Sneddon, Robert. *The World of the Cell: Life on a Small Scale.* Heinemann Library; 2003, Chicago.
- Wallace, Holly. *Cells and Systems.* Heinemann Library; 2001, Chicago.

Vocabulary

cell The smallest unit of an organism that is still considered living; the basic unit that make up every type of organism.

organ A group of tissues that work together to perform a common function.

organ system A group of organs that work together to perform a common function.

scanning electron microscope (SEM) Microscope that scans the surface of a tissue or cell, showing a 3D image.

tissue A group of specialized cells that function together.

transmission electron microscope (TEM) Microscope used to look at a very thin section of an organism and allow us to study the internal structure of cells.

Points to Consider

- Do you think there would be a significant difference between bacteria cells and your brain cells? What might they be?
- Do you think a bacteria cell and brain cell have some things in common? What might they be?
- Do you think cells are organized? What would be the benefit of organization?

3.2 Lesson 3.2: Cell Structures

Lesson Objectives

- Compare prokaryotic and eukaryotic cells.

- List the organelles of the cell and their functions.
- Discuss the structure and function of the cell membrane and cytosol.
- Describe the structure and function of the nucleus.
- Distinguish between plant and animal cells.

Check Your Understanding

- What is a cell?
- How do we visualize cells?

Introduction

Understanding the structure and function of cells is essential to understanding how living organisms work. Cell biology is central to all other fields of biology, including medicine. Many human diseases and disorders are caused by the malfunction of people's cells. Furthermore, toxins in the environment often act on specific cellular processes. The healthy functioning of the body and its organs is dependent on its smallest unit - the cell.

To better understand the biology of the cell, you will first learn to distinguish the two basic categories of all cells: prokaryotic and eukaryotic cells. You will also learn what makes a cell specialized; there are major differences between a "simple" cell, like a bacteria, and a "complex" cell, like a cell in your brain. To understand these differences, you need to first understand the basic components of the cell, which include the:

- Cell membrane
- Nucleus and chromosomes
- Other organelles

Prokaryotic and Eukaryotic Cells

There are two basic types of cells, **prokaryotic cells** (**Figure** 3.8), which include bacteria and archaea, and **eukaryotic cells** (**Figure** 3.9), which include all other cells. Prokaryotic cells are much smaller and simpler than eukaryotic cells; eukaryotic cells can be considered to be "specialized." Prokaryotic cells are surrounded by a **cell wall** that supports and protects the cell. In prokaryotic cells the DNA, the genetic material, forms a single large circle that coils up on itself. Prokaryotic cells also can contain extra small circles of DNA, known as **plasmids**. The two types of organisms consisting of prokaryotic cells belong to the domain Bacteria and the domain Archaea. These two domains were discussed in the *Introduction to Living Things* chapter.

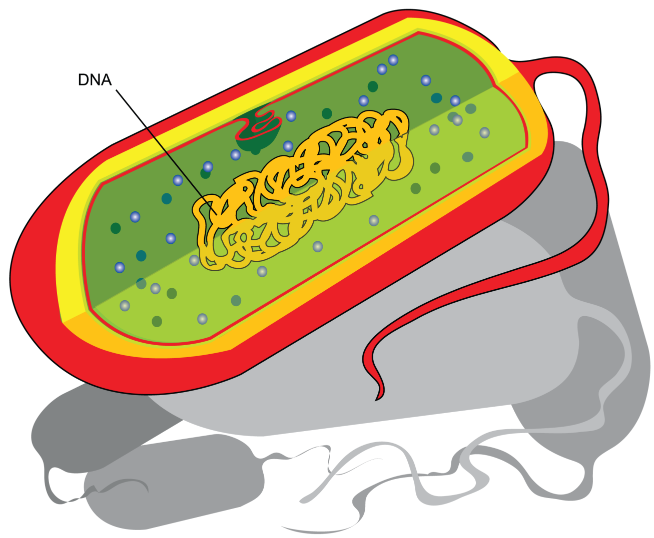

Figure 3.8: Prokaryotes do not have a nucleus. Instead, their genetic material is a simple loop of DNA. (6)

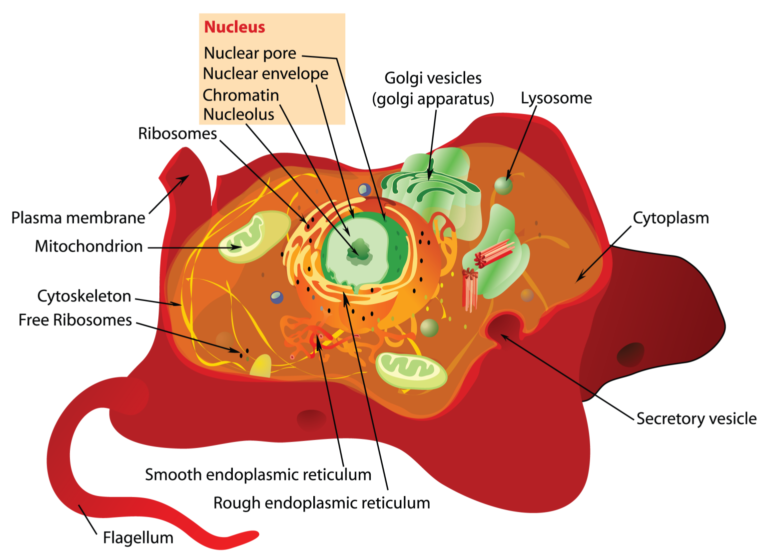

Figure 3.9: Eukaryotic cells contain a nucleus (where the DNA "lives," and surrounded by a membrane) and various other special compartments surrounded by membranes, called "organelles." For example, notice in this image the mitochondria, lysosomes, and peroxisomes. (7)

Table 3.1: **Comparison of Prokaryotic and Eukaryotic Cells**

Feature	Prokaryotic cells	Eukaryotic cells
DNA	Single "naked" circle; plasmids	In membrane-enclosed nucleus
Membrane-enclosed organelles	No	Yes
Examples	Bacteria	Plants, animals, fungi

The main difference between eukaryotic and prokaryotic cells is that eukaryotic cells store their DNA in a membrane-enclosed **nucleus**. The presence of a nucleus is the primary distinguishing feature of a eukaryotic cell. In addition to the nucleus, eukaryotic cells have other subcompartments, small membrane-enclosed structures called **organelles**. Membrane-enclosed organelles and a nucleus are absent in prokaryotic cells. Eukaryotic cells include the cells of fungi, animals, protists, and plants.

The Plasma Membrane and Cytosol

Both eukaryotic and prokaryotic cells have a plasma membrane. The **plasma membrane** is a double layer of specialized lipids, known as phospholipids, along with many special proteins. The function of the plasma membrane, also known as the "cell membrane," is to control what goes in and out of the cell.

Some molecules can go through the cell membrane in and out of the cell and some can't, so biologists say the membrane is **semipermeable**. It is almost as if the membrane chooses what enters and leaves the cell.

The cell membrane gives the cell an inside that is separate from the outside world. Without a cell membrane, the parts of a cell would just float away. A cell needs a boundary even more than we need our skin. Without a cell membrane, a cell would be unable to maintain a stable internal environment separate from the external environment, what we call homeostasis. You can learn more about cell membranes in the *Cell Functions* chapter.

Eukaryotic and prokaryotic cells also share an internal fluid-like substance called the **cytosol**. The cytosol is composed of water and other molecules, including enzymes that speed up the cell's chemical reactions. Everything in the cell - the nucleus and the organelles - sit in the cytosol. The term **cytoplasm** refers to the cytosol and all the organelles, but not the nucleus.

Table 3.2: **Some Eukaryotic Organelles**

Organelle	Function
Ribosomes	Involved in making proteins
Golgi apparatus	Packages proteins and some polysaccharides
Mitochondria	Makes ATP
Smooth ER	Makes lipids
Chloroplast	Makes sugar (photosynthesis)
Lysosomes	Digests macromolecules

The Nucleus and Chromosomes

The nucleus, which is found exclusively in eukaryotic cells, is a membrane-enclosed structure that contains most of the genetic material of the cell (**Figure** 3.10). Like a library, it holds vital information, mainly detailed instructions for building proteins. The **nuclear envelope**, a double membrane that surrounds the nucleus, controls which molecules go in and out of the nucleus.

Inside the nucleus are the chromosomes, the DNA all wrapped in special proteins. The genetic information on the chromosomes is stored made it available to the cell when necessary and also duplicated when it is time to pass the genetic information on when a cell divides. All the cells of a species carry the same number of chromosomes. For example, human cells each have 23 pairs of chromosomes. Each chromosome in turn carries hundreds or thousands of genes that encode proteins that help determine traits as varied as tooth shape, hair color, or kidney function.

The Cell Factory

Just as a factory is made up of many people, machines, and specific areas, each part of the whole playing a different role, a cell is also made up of different parts, each with a special role. For example, the nucleus of a cell is like a safe containing the factory's trade secrets, including how to build thousands of proteins, how much of each one to make, and when. The **mitochondria** are powerhouses that generate the ATP needed to power chemical reactions. Plant cells have special organelles called **chloroplasts** that capture energy from the sun and store it in the chemical bonds of sugar molecules - in the process called photosynthesis (**Figure** 3.11). (The cells of animals and fungi do not photosynthesize and do not have chloroplasts.)

The **vacuoles** are storage centers, and the **lysosomes** are the recycling trucks that carry waste away from the factory. Inside lysosomes are enzymes that break down old molecules into parts that can be recycled into new ones. Eukaryotic cells also contain and internal skeleton called the **cytoskeleton**. Like our bony skeleton, a cell's cytoskeleton gives the cell

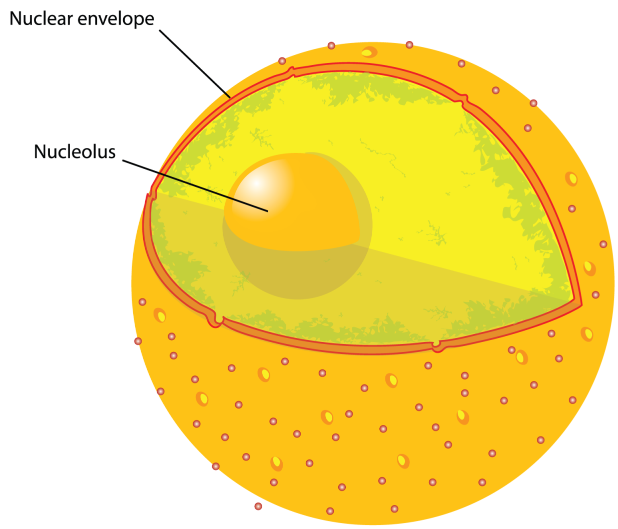

Figure 3.10: In eukaryotic cells, the DNA is kept in a nucleus. The nucleus is surrounded by a double plasma membrane called the **nuclear envelope**. Within the nucleus is the *nucleolus* (smaller yellow ball). (11)

a shape and helps it move parts of the cell.

In both eukaryotes and prokaryotes, **ribosomes** are where proteins are made. Some ribosomes cluster on folded membranes called the endoplasmic reticulum (ER). If the ER is covered with ribosomes, it looks bumpy and is called rough ER. If the ER lacks ribosomes, it is smooth and is called smooth ER. Proteins are made on rough ER and lipids are made on smooth ER.

Another set of folded membranes in cells is the **Golgi apparatus**, which works like a mail room. The Golgi apparatus receives the proteins from the rough ER, puts sugar molecule "shipping addresses" on the proteins, packages them up in vesicles, and then sends them to the right place in the cell.

Plant Cells

Even though plants and animals are both eukaryotes, plant cells differ in some ways from animal cells. First, plant cells are unique in having a large central **vacuole** that holds a mixture of water, nutrients, and wastes. A plant cell's vacuole can make up 90% of the cell's volume. In animal cells, vacuoles are much smaller.

Second, plant cells have a cell wall, which animal cells do not. A **cell wall** gives the plant cell strength, rigidity, and protection. Although bacteria and fungi also have cell

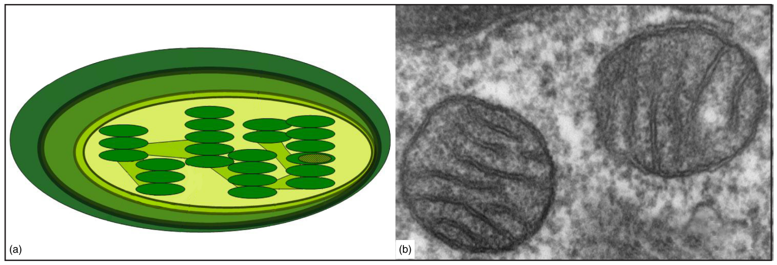

Figure 3.11: Diagram of chloroplast (a) and electron microscope image of two mitochondria (b). Chloroplasts and mitochondria provide energy to cells. If the bar at the bottom of the electron micrograph image is 200 nanometers, what is the diameter of one of the mitochondria? (10)

walls, a plant cell wall is made of a different material. Plant cell walls are made of the polysaccharides cellulose, fungal cell walls are made of chitin, and bacterial cell walls are made of peptidoglycan. This is highlighted in **Figure** 3.12.

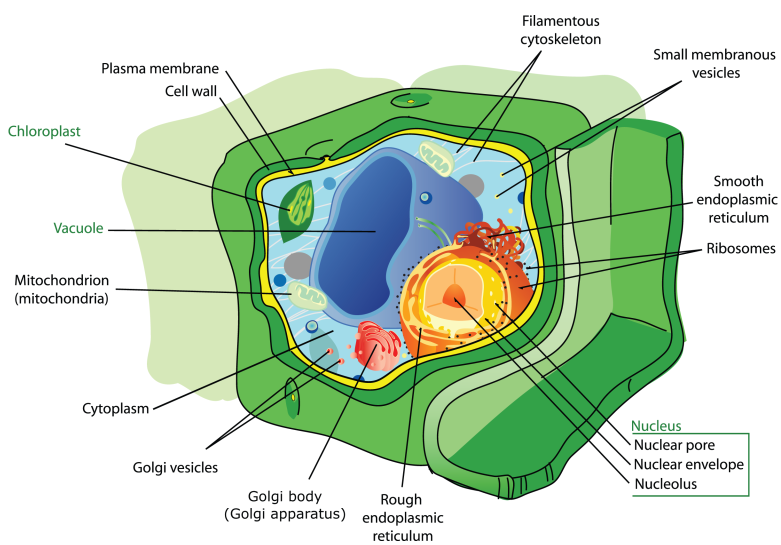

Figure 3.12: A plant cell has several features that make it different from an animal cell, including a cell wall, huge vacuoles, and several kinds of plastids, including chloroplasts (which photosynthesize). (5)

A third difference between plant and animal cells is that plants have several kinds of organelles called **plastids**. There are several kinds of plastids, including **chloroplasts**, needed for photosynthesis; **leucoplasts**, which store starch and oil; and brightly colored **chromoplasts**, which give some flowers and fruits their yellow, orange, or red color. You will learn more about chloroplasts and photosynthesis in the chapter titled *Cell Functions*. Under a microscope one can see plant cells more clearly (**Figure** 3.13).

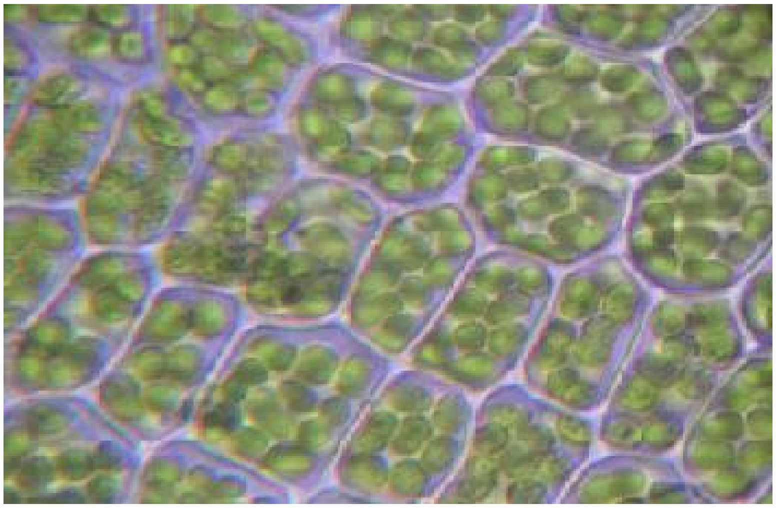

Figure 3.13: In this photo of plant cells taken with a light microscope, you can see a cell wall (purple) around each cell and green chloroplasts. (13)

Lesson Summary

- Prokaryotic cells lack a nucleus; eukaryotic cells have a nucleus.
- Each component of a cell has a specific function.
- Plant cells have unique features including plastids, cell walls, and central vacuoles.

Review Questions

1. What are the two basic types of cells?
2. What are organelles?
3. Discuss the main differences between prokaryotic cells and eukaryotic cells.
4. What is the plasma membrane and what is its role?
5. What organelle is known as the "powerhouse" of the cell?
6. Why does photosynthesis not occur in animal cells?
7. What are the main differences between a plant cell and an animal cell?

Further Reading / Supplemental Links

- Baeuerle, Patrick A. and Landa, Norbert. *The Cell Works: Microexplorers.* Barron's; 1997, Hauppauge, New York.
- Sneddon, Robert. *The World of the Cell: Life on a Small Scale.* Heinemann Library; 2003, Chicago.
- Wallace, Holly. *Cells and Systems.* Heinemann Library; 2001, Chicago.

Vocabulary

cell The smallest unit of an organism that is still considered living; the basic unit that make up every type of organism.

cell wall Provides strength and protection for the cell; found around plant, fungal, and bacterial cells.

central vacuole Large organelle containing water, nutrients, and wastes that can take up to 90% of a plant cell's volume.

chloroplast Green organelle that captures solar energy and stores the energy in sugars through the process of photosynthesis; chloroplasts are found only in cells that perform photosynthesis.

chromosome The cell structure in eukaryotic cells containing the genes; made of DNA and protein. Human cells have 23 pairs of chromosomes.

cytoplasm All the contents of the cell besides the nucleus, including the cytosol and the organelles.

cytoskeleton The internal scaffolding of the cell; maintains the cell shape and aids in moving the parts of the cell.

cytosol A fluid-like substance inside the cell; organelles are embedded in the cytosol.

endoplasmic reticulum (ER) A folded membrane organelle; rough ER modifies proteins and smooth ER makes lipids.

eukaryotic cell Cell belonging to the domain Eukarya (fungi, animals, protists, and plants); has a membrane-enclosed nucleus and various organelles.

golgi apparatus The organelle where proteins are modified, labeled, packaged into vesicles, and shipped.

homeostasis The ability to maintain a stable internal environment separate from the external environment.

lysosome Organelle which contains enzymes that break down unneeded materials.

mitochondria The organelle in all eukaryotic cells that makes adenosine triphosphate (ATP), the "energy currency" of cells.

nuclear envelope A double membrane that surrounds the nucleus; helps regulate the passage of molecules in and out of the nucleus.

nucleus Membrane enclosed organelle in eukaryotic cells that contains the DNA; primary distinguishing feature between a eukaryotic and prokaryotic cell; the information center, containing instructions for making all the proteins in a cell, as well as how much of each one.

organelle Small structure wrapped in a membrane found only in eukaryotic cells; mitochondria, plastids, and vacuoles, for example. A ribosome is not technically an organelle, because it is not enclosed in a membrane.

plasma membrane Surrounds the cell; made of a double layer of specialized lipids, known as phospholipids, with embedded proteins; regulates the movement of substances into and out of the cell; also called the cell membrane.

plasmid Small circular piece of DNA; found in prokaryotic cells.

prokaryotic cell Cell with no nucleus or other membrane-enclosed organelles; bacteria and archaea.

ribosome The cell structure on which proteins are made; not surrounded by a membrane; found in both prokaryotic and eukaryotic cells.

rough endoplasmic reticulum The part of the ER with ribosomes attached; proteins can be modified in the rough ER before they are packed into vesicles for transport to the golgi apparatus.

semi-permeable allowing only certain materials to pass through; characteristic of the cell membrane.

smooth endoplasmic reticulum Part of the ER that does not have ribosomes attached; where lipids are synthesized.

vesicle Small membrane-enclosed sac; transports proteins around a cell or out of a cell.

Points to Consider

- Think about what molecules would need to be transported into cells.
- Discuss why it would be important for some molecules to be kept out of a cell.

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Chapter 4

Cell Functions

4.1 Lesson 4.1: Transport

Lesson Objectives

- Describe several methods of transporting molecules and ions into and out of the cell.
- Distinguish between active and passive transport.
- Explain how diffusion and osmosis work.

Check Your Understanding

- What structure surrounds the cell?
- What is the primary component of the cell membrane?
- What does homeostasis mean?

Introduction

All organisms and their cells need to maintain homeostasis. But how can a cell keep a stable internal environment when the environment around the cell is constantly changing? Obviously, the cell needs to separate itself from the external environment. This job is accomplished by the cell membrane. The cell membrane is **selectively permeable,** or "semipermeable," which means that only some molecules can get through the membrane. If the cell membrane was completely permeable, the inside of the cell would be about the same as the outside and the cell could not achieve homeostasis.

How does the cell maintain this selective permeability? How does the cell control what molecules enter and leave the cell? The ways that cells control what passes through the cell membrane will be the focus of this lesson.

What is Transport?

The selectively permeable nature of the plasma membrane is due in part to the chemical composition of the membrane. Recall that the membrane is a double layer of phospholipids (a "bilayer") embedded with proteins (**Figure** 4.1). A single phospholipid molecule has a hydrophilic, or water-loving, head and hydrophobic, or water-fearing, tail. The hydrophilic heads face the inside and outside of the cell, where water is abundant. The water-fearing, hydrophobic tails face each other in the middle of the membrane. At body temperature, the plasma membrane is fluid and constantly moving, like a soap bubble; it is not a solid structure.

Water and small non-charged molecules such as oxygen and carbon dioxide can pass freely through the membrane by slipping around the phospholipids. But larger molecules and charged molecules cannot pass through the plasma membrane easily. Therefore, special methods are needed for transporting some molecules across the plasma membrane and into or out of the cell.

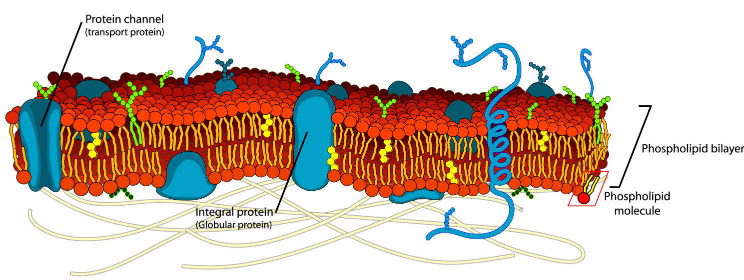

Figure 4.1: The plasma membrane is made up of a phospholipid bilayer with embedded proteins. (9)

Since atoms have an equal number of protons and electrons, they have no net charge. The negative charges of the electrons balance out the positive charges of the protons. Many molecules have an equal number of electrons and protons, so we call them non-polar molecules. However, some atoms can lose or gain electrons easily, giving them a positive or negative charge. These charged particles are called **ions.** If an atom loses an electron, it becomes a positively charged ion, such as the sodium ion Na^+. If an atom gains an electron, it will be a negatively charged ion, such as the chloride ion, Cl^-. Na^+ and Cl^- readily form NaCl, or common table salt. Since Na^+ and Cl^- are charged, they are unable to pass freely through the plasma membrane.

Passive Transport

Small molecules can pass through the plasma membrane through a process called diffusion. **Diffusion** is the movement of molecules from an area where there is a higher concentration (larger amount) of the substance to an area where there is a lower concentration (lower amount) of the substance. The amount of a substance in relation to the volume, is called **concentration**. Diffusion requires no energy input from the cell (**Figure** 4.2). Diffusion occurs by the random movement of molecules; molecules move in both directions (into and out of the cell), but there is a greater movement from an area of higher concentration towards an area of lower concentration. The movement of the substance from a greater concentration to a lesser concentration is referred to as moving down the concentration gradient. For example, oxygen diffuses out of the air sacs in your lungs into your bloodstream because oxygen is more concentrated in your lungs than in your blood. Oxygen moves down the concentration gradient from your lungs into your bloodstream

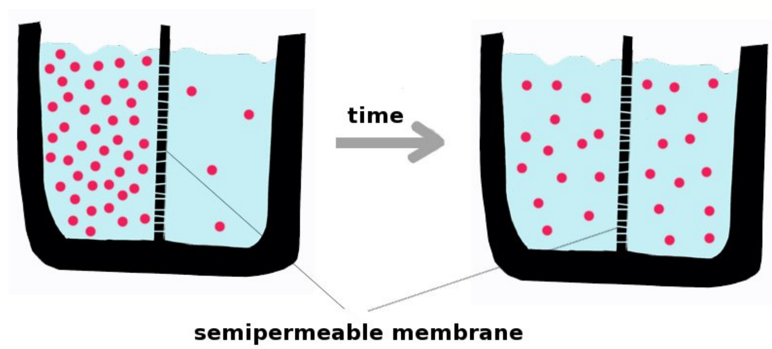

Figure 4.2: Diffusion across a membrane does not require an input of energy. (2)

The diffusion of water across a membrane due to concentration differences is called **osmosis.** If a cell is placed in a **hypotonic solution,** meaning the solution has a lower concentration of dissolved material than what is inside the cell, water will move into the cell. This causes the cell to swell, and it may even burst. Organisms that live in fresh water, which is a hypotonic solution, have to prevent too much water from coming into their cells. Freshwater fish excrete a large volume of dilute urine to rid their bodies of excess water.

If a cell is placed in a **hypertonic solution,** meaning there is more dissolved material in the outside environment than in the cell, water will leave the cell. That can cause a cell to shrink and shrivel. Marine animals live in salt water, which is a hypertonic environment; there is more salt in the water than in their cells. To prevent losing too much water from their bodies, these animals intake large quantities of salt water and secrete salt by active transport, which will be discussed later in this lesson.

To keep cells intact, they need to be placed in an **isotonic solution,** a solution in which the amount of dissolved material is equal both inside and outside the cell. Therefore, there is no net movement of water into or out of the cell. Water still flows in both directions, but an equal amount enters and leaves the cell. In the medical setting, red blood cells can be kept intact in a solution that is isotonic to the blood cells. If the blood cells were put in pure water, the solution would be hypotonic to the blood cells, so the blood cells would swell and burst. This is represented in the **Figure** 4.3.

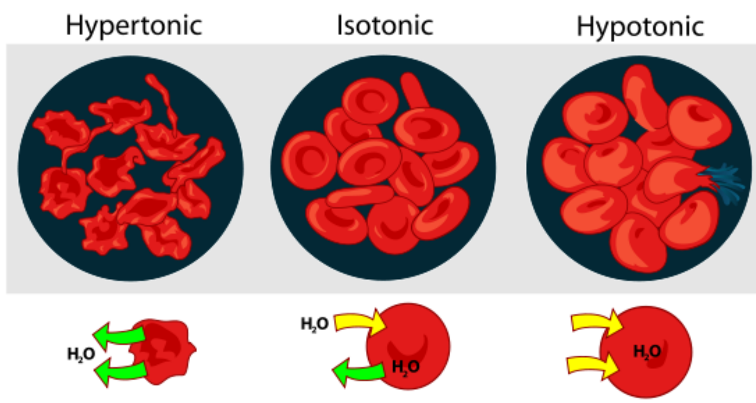

Figure 4.3: Osmosis causes these red blood cells to change shape by losing or gaining water. (1)

Sometimes diffusion across the membrane is slow or even impossible for some charged or large molecules. These molecules need the help of special helper proteins that are located in the plasma membrane. **Ion channel proteins** move ions across the plasma membrane. Other molecules, such as glucose, move across the cell membrane by **facilitated diffusion,** in which a carrier protein physically moves the molecule across the membrane (**Figure** 4.4). Both channel proteins and carrier proteins are specific for the molecule transported. Movement by ion channel proteins and facilitated diffusion are still considered **passive transport,** meaning they move molecules down the cell's concentration gradient and do not require any energy input.

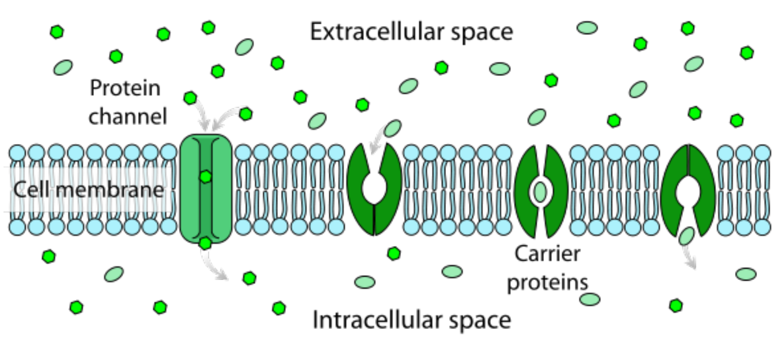

Figure 4.4: Facilitated Diffusion is a type of passive transport where a carrier protein aids in moving the molecule across the membrane. (11)

Active Transport

During active transport, molecules move against the concentration gradient, toward the area of higher concentration. This is the opposite of diffusion. Active transport requires both an input of energy, in the form of ATP, and a carrier protein to move the molecules. These proteins are often called pumps, because, as a water pump uses energy to force water against gravity, proteins involved in active transport use energy to move molecules against their concentration gradient.

There are many examples of why active transport is important in your cells. One example occurs in your nerve cells. In these cells, the **sodium-potassium pump** (**Figure** 4.5) moves sodium outside the cell and potassium into the cell, both against their concentration gradients.

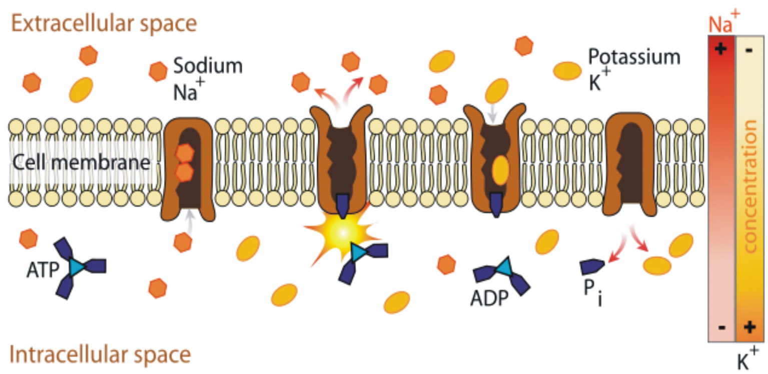

Figure 4.5: The sodium-potassium pump moves sodium ions to the outside of the cell and potassium ions to the inside of the cell. ATP is required for the protein to change shape. As ATP adds a phosphate group to the protein, it leaves behind adenosine diphosphate (ADP). (14)

Transport Through Vesicles

Some large molecules are just too big to move across the membrane, even with the help of a carrier protein. These large molecules must be moved through vesicle formation, a process by which the large molecules are packaged in a small bubble of membrane for transport. This process keeps the large molecules from reacting with the cytoplasm of the cell. Vesicle formation does require an input of energy, however.

There are several kinds of vesicle formation that allow large molecules to move across the plasma membrane. **Exocytosis** moves large molecules outside of the cell. During exocytosis, the vesicle carrying the large molecule fuses with the plasma membrane. The large molecule is then released outside of the cell, and the vesicle is absorbed into the plasma membrane. **Endocytosis** is the process by which cells take in large molecules by vesicle formation. Types of endocytosis include phagocytosis and pinocytosis. **Phagocytosis** moves large substances, even another cell, into the cell. Phagocytosis occurs frequently in single-celled organisms, such as amoebas. **Pinocytosis** (**Figure** 4.6) involves the movement of liquid or very small particles into the cell. These processes cause some membrane material to be lost as these vesicles bud off and come into the cell. This membrane is replaced by the membrane gained through exocytosis.

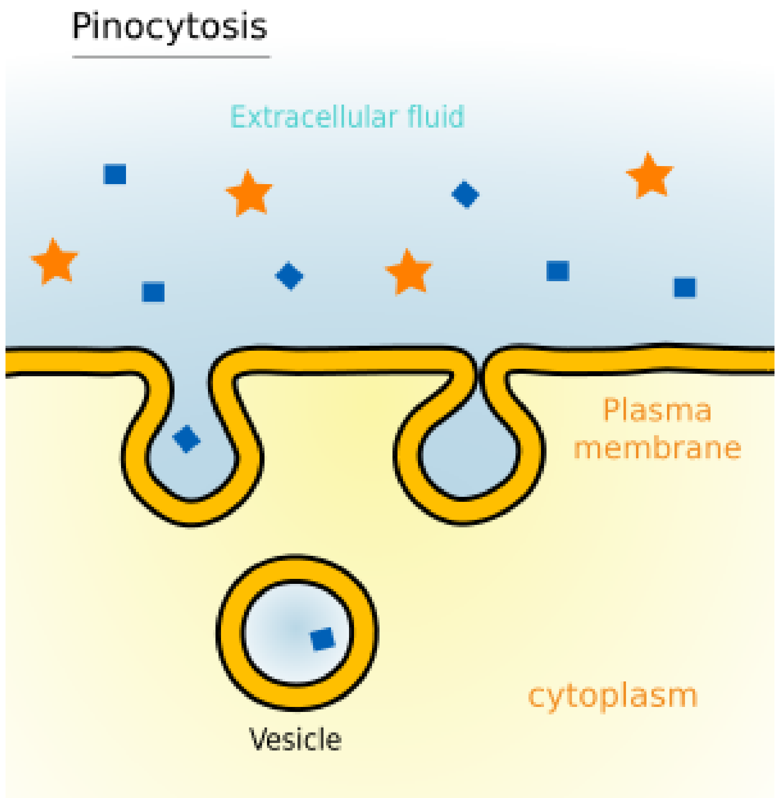

Figure 4.6: During endocytosis, exocytosis and pinocytosis, substances are moved into or out of the cell via vesicle formation. (13)

Lesson Summary

- The plasma membrane is selectively permeable or semi-permeable, meaning that some molecules can move through the membrane easily, while others require specialized transport mechanisms.
- Passive transport methods, including diffusion, ion channels, facilitated diffusion, and osmosis, move molecules in the direction of the lowest concentration of the molecule and do not require energy.

- Active transport methods move molecules in the direction of the higher concentration and require energy and a carrier protein.
- Vesicles can be used to move large molecules, which requires energy input.

Review Questions

1. What happens when a cell is placed in a hypotonic solution?
2. What happens when a cell is placed in a hypertonic solution?
3. What's the main difference between active and passive transport?
4. List an example of active transport.
5. List the types of passive transport.
6. Why is the plasma membrane considered semipermeable?
7. What is the process where a cell engulfs a macromolecule, forming a vesicle?
8. What is diffusion?
9. Explain the results of a sodium-potassium pump working across a membrane.
10. Does facilitated transport move a substance down or up a gradient?

Further Reading / Supplemental Links

- http://www.vivo.colostate.edu/hbooks/cmb/cells/pmemb/passive.html
- http://www.vivo.colostate.edu/hbooks/molecules/sodium_pump.html
- http://www.biologycorner.com/bio1/diffusion.html
- http://www.northland.cc.mn.us/biology/Biology1111/animations/transport1.html
- http://www.brookscole.com/chemistry_d/templates/student_resources/shared_resources/animations/ion_pump/ionpump.html
- http://www.enwikipedia.org/

Vocabulary

active transport Moving a molecule from an area of lower concentration to an area of higher concentration; requires a carrier protein and energy.

concentration The amount of a substance in relation to the volume.

diffusion Movement of molecules from an area of high concentration to an area of low concentration; requires no energy.

endocytosis Movement of substances into the cell by vesicle formation.

exocytosis Movement of substances out of the cell by a vesicle fusing with the plasma membrane.

facilitated diffusion Diffusion in which a carrier protein physically moves the molecule across the membrane; a form of passive transport.

homeostasis Maintaining a stable internal environment despite any external changes.

hypertonic solution Having a higher solute concentration than the cell; cell will lose water by osmosis.

hypotonic solution Having a lower solute concentration than the cell; cell will gain water by osmosis.

ion An atom that carries a negative or positive charge.

ion channel Protein in the plasma membrane that allows ions to pass through.

isotonic solution A solution in which the amount of dissolved material is equal both inside and outside the cell; no net gain or loss of water.

osmosis Diffusion of water across a membrane.

passive transport Movement of molecules from an area of higher concentration to an area of lower concentration; requires no energy.

phagocytosis Movement of large substances, including other cells, into the cell by vesicle formation.

phospolipid A lipid molecule with a hydrophilic head and two hydrophobic tails; makes up the cell membrane.

pinocytosis Movement of macromolecules into the cell by vesicle formation.

selectively permeable Semipermeable; property of allowing only certain molecules to pass through the cell membrane.

sodium-potassium pump Carrier protein that moves sodium ions out of the cell and potassium ions into the cell; works against the concentration gradient and requires energy.

vesicle formation The formation of a small membrane-bound sac that can store and move substances into and out of the cell.

Points to Consider

- The next lesson discusses photosynthesis.
- It is often said that plants make their own food. What do you think this means?
- What substances would need to move into a leaf cell?
- What substances would need to move out of a leaf cell?

4.2 Lesson 4.2: Photosynthesis

Lesson Objectives

- Explain the importance of photosynthesis.
- Write and interpret the chemical equation for photosynthesis.
- Describe what happens during the light reactions and the Calvin Cycle.

Check Your Understanding

- How are plant cells different from animal cells?
- In what organelle does photosynthesis take place?

Introduction

Almost all life on Earth depends on photosynthesis. Recall that photosynthesis is the process by which plants use the sun's energy to make their own "food" from carbon dioxide and water. For example, animals, such as caterpillars, eat plants and therefore rely on the plants to obtain energy. If a bird eats a caterpillar, then the bird is obtaining the energy that the caterpillar gained from the plants. So the bird is indirectly getting energy that began with the "food" formed through photosynthesis. Almost all organisms obtain their energy from photosynthetic organisms, either directly, by eating photosynthetic organisms, or indirectly by eating other organisms that ultimately obtained their energy from photosynthetic organisms. Therefore, the process of photosynthesis is central to sustaining life on Earth.

Overview of Photosynthesis

Photosynthesis is the process that converts the energy of the sun, or solar energy, into carbohydrates, a type of chemical energy. During photosynthesis, carbon dioxide and water combine with solar energy, yielding glucose (the carbohydrate) and oxygen. As mentioned previously, plants can photosynthesize, but plants are not the only organisms with this ability. Algae, which are plant-like protists, and cyanobacteria (certain bacteria which are also known as blue-green bacteria, or blue-green algae) can also photosynthesize. Algae and cyanobacteria are important in aquatic environments as sources of food for larger organisms.

Photosynthesis mostly takes place in the leaves of a plant. The green pigment in leaves, **chlorophyll,** helps to capture solar energy. And special structures within the leaves provide water and carbon dioxide, which are the raw materials for photosynthesis. The veins within a leaf carry water which originates from the roots, and carbon dioxide enters the leaf from the air through special pores called **stomata** (**Figure** 4.7).

Figure 4.7: Stomata are special pores that allow gasses to enter and exit the leaf. (4)

The water and carbon dioxide are transported within the leaf to the **chloroplast** (**Figure** 4.8), the organelle in which photosynthesis takes place. The chloroplast has two distinct membrane systems; an outer membrane surrounds the chloroplast and an inner membrane system forms flattened sacs called **thylakoids.** As a result, there are two separate spaces within the chloroplast. The interior space that surrounds the thylakoids is filled with a fluid called **stroma.** The inner compartments formed by the thylakoid membranes are called the thylakoid space.

The overall chemical reaction for photosynthesis is 6 molecules of carbon dioxide (CO_2) and 6 molecules of water (H_20), with the addition of solar energy, yields 1 molecule of glucose ($C_6H_{12}O_6$) and 6 molecules of oxygen (O_2). Using chemical symbols the equation is represented as follows:

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

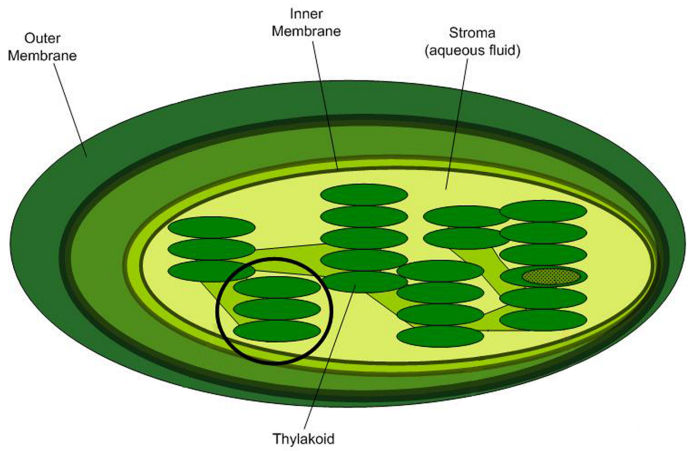

Figure 4.8: The chloroplast is the photosynthesis factory of the plant. (7)

Oxygen: An Essential Byproduct

Oxygen is a byproduct of the process of photosynthesis and is released to the atmosphere through the stomata. Therefore, plants and other photosynthetic organisms play an important ecological role in converting carbon dioxide into oxygen. As you know, animals need oxygen to carry out the energy-producing reactions of their cells. Without photosynthetic organisms, many other organisms would not have enough oxygen in the atmosphere to survive. Oxygen is also used as a reactant in cellular respiration, which is discussed in the next lesson, so essentially, oxygen cycles through the processes of photosynthesis and cellular respiration.

The Light Reactions and the Calvin Cycle

The overall process of photosynthesis does not happen in one step, however. The chemical equation of photosynthesis shows the results of many chemical reactions. The chemical reactions that make up the process of photosynthesis can be divided into two groups: the light reactions (also known as the light-dependent reactions, because these reactions only occur during daylight hours) and the Calvin Cycle, or the light-independent reactions. During the **light reactions**, the energy of sunlight is captured, while during the **Calvin Cycle**, carbon dioxide is converted into glucose, which is a type of sugar. This is summarized in **Figure** 4.9.

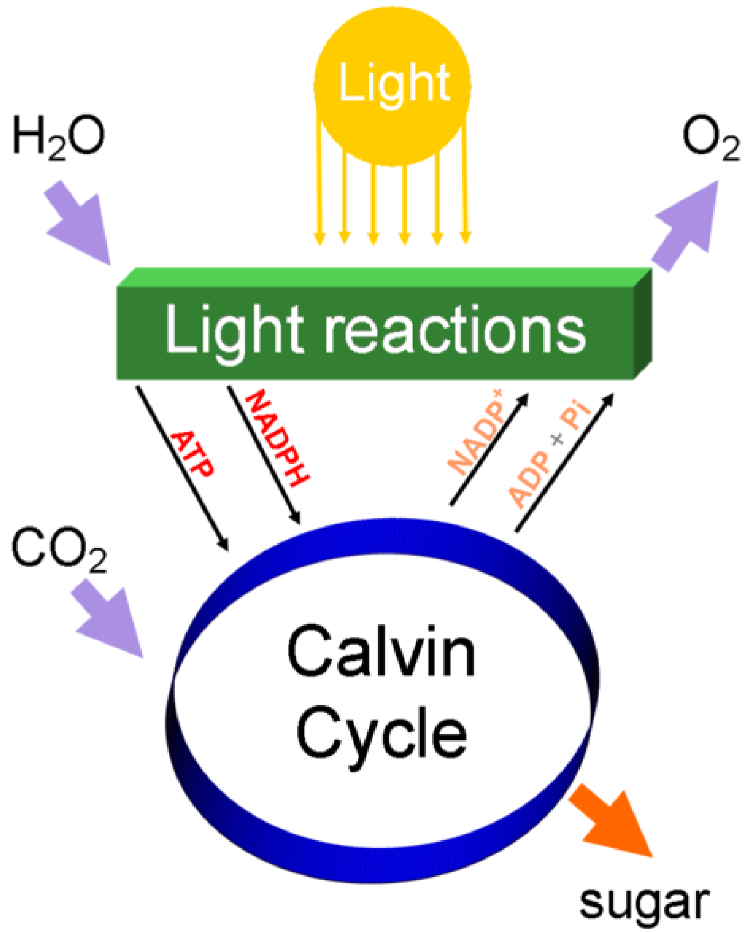

Figure 4.9: This overview of photosynthesis shows that light is captured during the light reactions, resulting in the production of ATP and the electron carrier NADPH. Through the Calvin Cycle, these materials are used to fix carbon dioxide into sugar. Also during the Calvin Cycle, $NADP^+$ and ADP are regenerated. (3)

Stage 1: Capturing Light Energy

In the first step of the light reactions, solar energy is absorbed by the chlorophyll (and accessory pigments) within the chloroplast's thylakoid membranes. This absorbed energy excites electrons in the thylakoid membranes. The electrons are then transferred from the thylakoid membranes by a series of electron carrier molecules. The series of electron carrier molecules that transfers electrons is called the electron transport chain. During this process water molecules in the thylakoid are split to replace the electrons that left the pigment, releasing oxygen and adding hydrogen ions (H^+) to the thylakoid space. As the thylakoid becomes a reservoir for hydrogen ions, a **chemiosmotic gradient** forms as there are more hydrogen ions in the thylakoid than in the stroma. As H^+ ions flows from the high concentration in the thylakoid to the low concentration in the stroma, they provide energy as they pass through an enzyme called ATP synthase. ATP synthase uses the energy of the movement of H^+ ions to make ATP. Meanwhile, highly energized electrons from the electron transport chain combine with the electron carrier $NADP^+$ to become NADPH (**Figure** 4.10). NADPH will carry this energy in the electrons to the next phase of photosynthesis, the Calvin Cycle.

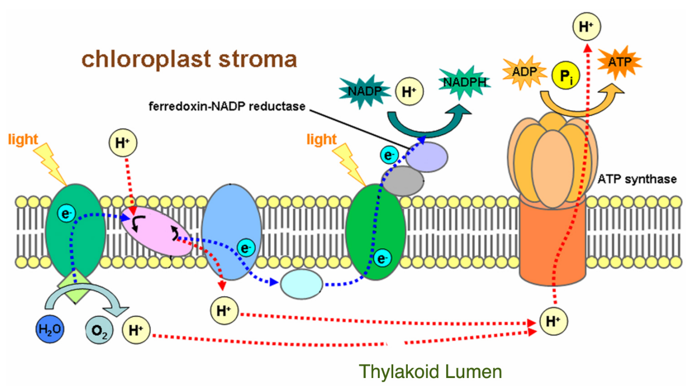

Figure 4.10: The light reactions includes the movement of electrons down the electric transport chain, splitting water and releasing hydrogen ions into the thylakoid space. (5)

Stage 2: Producing Food

During the Calvin Cycle, which occurs in the stroma of the chloroplast, glucose is formed from carbon dioxide and the products of the light reactions. During the first step CO_2 is attached to a 5-carbon molecule (called Ribulose-5-Phosphate, RuBP), forming a 6-carbon molecule. This reaction is catalyzed by an enzyme named RuBisCo, which is the most abundant protein in plants and maybe on Earth! The 6-carbon molecule formed by this reaction immediately splits into two 3-carbon molecules, and the 3-carbon molecule is rearranged to a 3-carbon carbohydrate. The energy and electrons needed for this process are provided by the ATP and

NADPH produced earlier in photosynthesis. The "food" made by photosynthesis is formed from the 3-carbon carbohydrate. Two 3-carbon carbohydrates combine to form glucose, a 6-carbon carbohydrate. Next, the 6-carbon RuBP must be reproduced so the Calvin Cycle can start again (**Figure** 4.11).

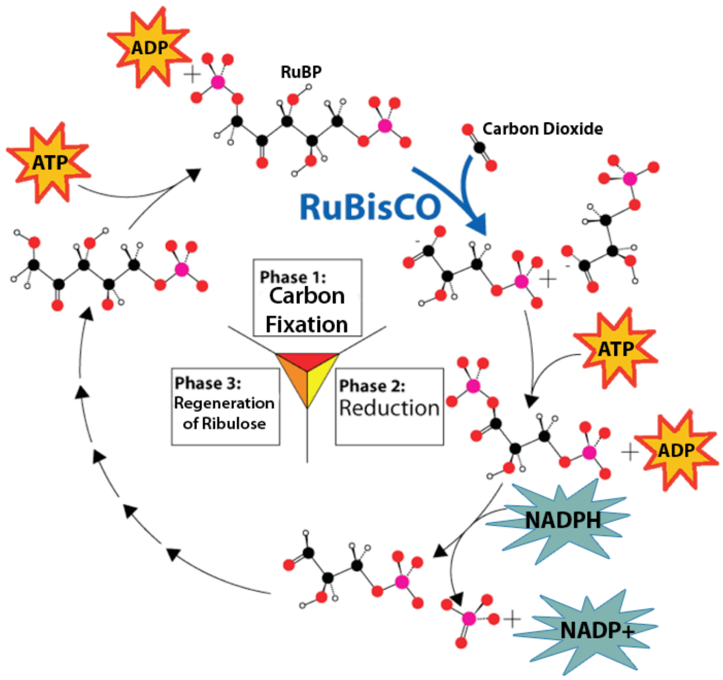

Figure 4.11: The Calvin Cycle begins with carbon fixation, or carbon dioxide attaching to the 5-carbon molecule RuBP, forming a 6-carbon molecule and splitting immediately in to two 3-carbon molecules. This is shown at the top of the figure. This carbon molecule is then reduced to a 3-carbon carbohydrate, shown at the bottom of the figure. The energy and reducing power needed for this process are provided by the ATP and NADPH produced from the light reactions. Next, RuBP must be reproduced so the Calvin Cycle can continue. *The carbons are the small black circles. You can keep track of the number of carbons at each stage by counting these circles.* (10)

The 3-carbon product of the Calvin Cycle can be converted into many types of organic molecules. Glucose, the energy source of plants and animals, is only one possible product of photosynthesis. Glucose is formed by two turns of the Calvin Cycle. Glucose can be formed into long chains as **cellulose**, a structural carbohydrate, or **starch**, a long-term storage carbohydrate. The product of the Calvin Cycle can also be used as the backbone of fatty acids, or amino acids, which make up proteins.

Photosynthesis is crucial to most ecosystems since animals obtain energy by eating other animals, or plants and seeds that contain these organic molecules. In fact, it is the process of photosynthesis that supplies almost all the energy to an ecosystem.

Lesson Summary

- The net reaction for photosynthesis is that carbon dioxide and water, together with energy from the sun, produce glucose and oxygen.
- During the light reactions of photosynthesis, solar energy is converted into the chemical energy of ATP and NADPH.
- During the Calvin Cycle, the chemical energy of ATP and NADPH is used to convert carbon dioxide into glucose.

Review Questions

1. What is the energy-capturing stage of photosynthesis?
2. What are the products of the light reactions?
3. What are the ATP and NADPH from the light reactions used for?
4. Where does the oxygen released by photosynthesis come from?
5. What happens to the glucose produced from photosynthesis?
6. Describe the structures of the chloroplast where photosynthesis takes place.
7. What is the significance of the electron transport chain?
8. What are the reactants required for photosynthesis?
9. What are the products of photosynthesis?

Further Reading / Supplemental Links

- http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookPS.html
- http://photoscience.la.asu.edu/photosyn/education/photointro.html
- http://www.pbs.org/wgbh/nova/methuselah/photosynthesis.html
- http://www.science.smith.edu/departments/Biology/Bio231/ltrxn.html
- http://www.biology4all.com/resources_library/details.asp?ResourceID=43
- http://www.enwikipedia.org/

Vocabulary

ATP synthase An enzyme that uses the energy of the movement of H^+ ions to make ATP.

Calvin Cycle The reactions of photosynthesis in which carbon dioxide is converted into glucose, which is a type of sugar; also known as the light independent reactions.

chlorophyll Green pigment in leaves; helps to capture solar energy.

chloroplast The organelle in which photosynthesis takes place.

cyanobacteria Photosynthetic bacteria; also known as blue-green bacteria, or blue-green algae.

electron transport chain A series of electron carrier molecules that transfers electrons.

light reactions The reactions of photosynthesis that only occur during daylight hours in which the energy of sunlight is captured; also known as the light-dependent reactions.

NADPH A high energy electron carrier produced during the light reactions; carries the energy in the electrons to the Calvin Cycle.

photosynthesis The process by which plants use the sun's energy to make their own "food" from carbon dioxide and water; process that converts the energy of the sun, or solar energy, into carbohydrates, a type of chemical energy.

stomata Special pores in leaves; carbon dioxide enters the leaf and oxygen exits the leaf through these pores.

stroma Fluid in the chloroplast interior space; surrounds the thylakoids.

thylakoid Flattened sacs within the chloroplast; formed by the inner membranes.

Points to Consider

- How is glucose turned into an usable form of energy called ATP?
- How do you gain energy from the food you eat?
- What would provide more energy- a bowl of pasta or a small piece of candy?
- What "waste" gas do you exhale?

4.3 Lesson 4.3: Cellular Respiration

Lesson Objectives

- Write and explain the chemical formula for cellular respiration.
- Explain the two states of cellular respiration.
- Compare photosynthesis with cellular respiration.
- Describe the results of fermentation and understand when fermentation is needed.

Check Your Understanding

- Where does the energy captured at the beginning of photosynthesis originate from?
- What is the form of chemical energy produced by photosynthesis?
- What occurs in oxidation and reduction reactions?

Introduction

How does the food you eat provide energy? When you need a quick boost of energy, you might reach for an apple or a candy bar. Although foods with sugars can give you a quick boost of energy, they cannot be used for energy directly by your cells. Energy is simply stored in these foods. Through the process of **cellular respiration,** the energy in food is converted into energy that can be used by the body's cells. In other words, glucose (and oxygen) is converted into ATP (and carbon dioxide and water). ATP is the molecule that provides energy for your cells to perform work, such as contracting your muscles as you walk down the street or performing active transport. Cellular respiration is simply a process that converts one type of chemical energy, the energy stored in sugar, into another type, ATP.

Overview of Cellular Respiration

Most often, cellular respiration proceeds by breaking down glucose into carbon dioxide and water. As this breakdown of glucose occurs, energy is released. The process of cellular respiration includes the conversion of this energy into ATP. The overall reaction for cellular respiration is as follows:

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

Notice that the equation for cellular respiration is the direct opposite of photosynthesis. While water was broken down to form oxygen during photosynthesis, in cellular respiration oxygen is combined with hydrogen to form water. While photosynthesis requires carbon dioxide and releases oxygen, cellular respiration requires oxygen and releases carbon dioxide. This exchange of carbon dioxide and oxygen in all the organisms that use photosynthesis and/or cellular respiration worldwide, helps to keep atmospheric oxygen and carbon dioxide at somewhat stable levels.

Cellular respiration doesn't happen all at once, however. Glucose is broken down slowly so that cells convert as much sugar as possible into the usable form of energy, ATP. Still, some energy is lost in the process in the form of heat. When one molecule of glucose is broken down, it can be converted to a net total of 36 or 38 molecules of ATP. Although the process is not 100% efficient, it is much more efficient than a car engine obtaining energy from gasoline.

Cellular respiration can be divided into three phases.

1. Glycolysis: the breakdown of glucose.
2. The citric acid cycle: the formation of electron carriers.
3. The electron transport chain: the formation of ATP.

In eukaryotic cells, the first phase takes place in the cytoplasm of the cell, while the other phases are carried out in the mitochondria. This organelle is known as the “powerhouse” of the cell because this is the organelle where the ATP that powers the cell is produced.

Glycolysis

The first step of cellular respiration is glycolysis. During **glycolysis,** the 6-carbon glucose is practically ”cut in half,” broken down into two 3-carbon pyruvate molecules. Glycolysis requires an initial energy-investment step, although in the end, glycolysis produces more energy than was initially invested. Two ATP molecules are used to convert glucose into the two 3-carbon pyruvate molecules. These 3-carbon molecules are then oxidized, which means that they lose electrons, as electrons are transferred to the high energy electron acceptor NAD^+, producing the electron carrier NADH. This oxidation step helps produce 4 ATP molecules from ADP. That means, taking into account the initial investment of 2 ATP molecules, glycolysis has a net production of 2 ATP.

Table 4.1: **An Overview of Glycolysis**

Inputs	Outputs
Glucose (6-carbon molecule)	2 pyruvate (3-carbon molecule)
2 NAD^+	2 NADH (electron carrier)
2 ATP (energy)	2 ADP
4 ADP	4 ATP (energy)

After glycolysis, the pyruvate can go down several different paths. If there is oxygen available, the pyruvate moves inside the mitochondrion to produce more ATP during further breakdown stages. In the absence of oxygen, the fermentation process begins.

Inside the Mitochondria

If oxygen is available, the next step of cellular respiration is moving the pyruvate into the mitochondria. The mitochondria have a double membrane. The inner membrane is known as the **cristae**, and is folded to form many internal layers. Some steps of cellular respiration occur in the cristae, while others take place in the **matrix**, the inner compartment of the mitochondrion that is filled with enzymes in a gel-like fluid.

Within the mitochondria the **Kreb’s Cycle** or **citric acid cycle** occurs. The citric acid

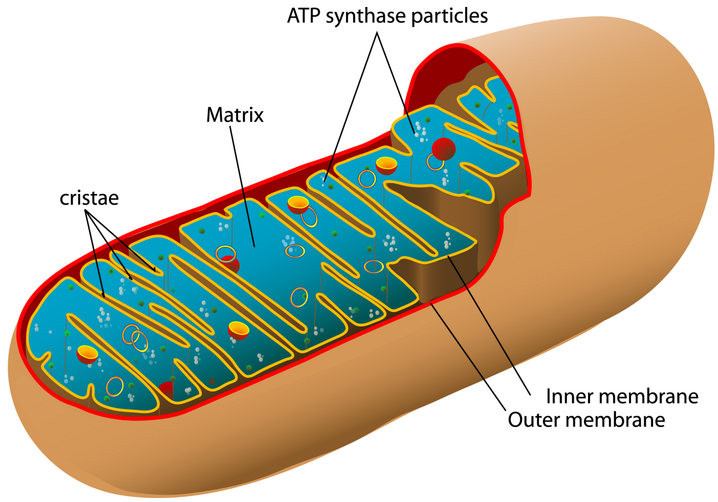

Figure 4.12: Most of the reactions of cellular respiration are carried out in the mitochondria. (6)

cycle is a series of oxidation steps that produce NADH and $FADH_2$, another type of electron carrier. These electron carriers will be used in the final step of cellular respiration. To begin the Kreb's Cycle, the 3-carbon pyruvate from glycolysis must be converted into a 2-carbon molecule, which then can enter the cycle. During the cycle carbon dioxide is produced. Two molecules of ATP are also produced per each initial glucose molecule. A graphic of the mitochondria is shown in **Figure** 4.12.

In the final steps of cellular respiration, the **electron transport chain** accepts the electrons from glucose that are being carried by NADH and $FADH_2$. These electrons are passed along the chain until they are finally combined with oxygen, which with the addition of hydrogen ions, becomes water. That is the key reason why this process only occurs in the presence of oxygen. Illustrated in **Figure** 4.13.

As the electrons move down the electron transport chain, energy is released and later used to synthesize ATP. The process of ATP synthesis is exactly the same as photosynthesis; hydrogen ions are pumped across the cristae of the mitochondria, forming a chemiosmotic gradient, and ATP synthase uses the energy of the movement of hydrogen ions back across the membrane, from high to low concentration, to make ATP.

Because oxygen is the final electron acceptor in this process, the electron transport chain can only occur in the presence of oxygen. This is known as **aerobic** respiration. However, there is not always enough oxygen present for aerobic respiration to occur. In this case, the next step after glycolysis will be fermentation instead of the citric acid cycle.

Table 4.2: **An Overview of the Citric Acid Cycle**

Inputs	Outputs
2 two-carbon molecules	4 CO_2
6 NAD^+	6 NADH (electron carrier)
2 FAD^+	2 $FADH_2$ (electron carrier)
2 ADP	2 ATP (energy)

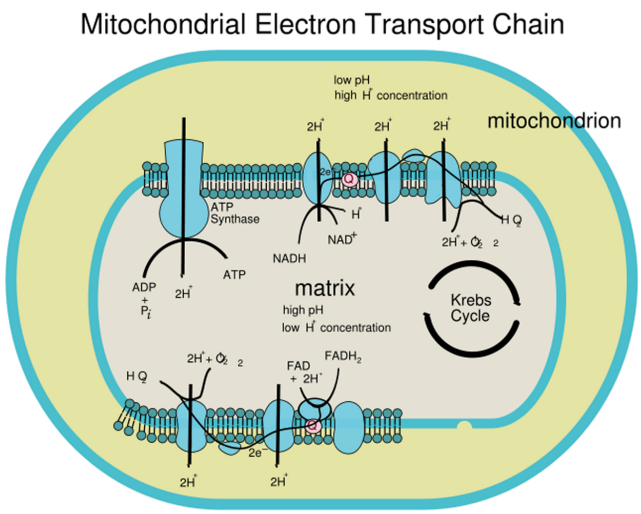

Figure 4.13: During electron transport, electrons from glucose (carried by NADH and $FADH_2$) are passed along until they are finally combined with oxygen, which with the addition of hydrogen ions, becomes water. Meanwhile, hydrogen ions are pumped across the cristae of the mitochondria, forming a gradient, and ATP synthase uses the energy of the movement of hydrogen ions back across the membrane, from high to low concentration, to make ATP. (8)

Fermentation

Sometimes cellular respiration is **anaerobic**, occurring in the absence of oxygen. In the process of **fermentation,** the NAD^+ is recycled so that is can be reused in the glycolysis process. No additional ATP is produced during fermentation, so the organism only obtains the two net ATP molecules per glucose from glycolysis.

Yeasts (single-celled eukaryotic organisms) carry on **alcoholic fermentation** in the absence of oxygen, making ethyl alcohol (drinking alcohol) and carbon dioxide. Alcoholic fermentation is central to bread baking. The carbon dioxide bubbles allow the bread to rise, and the alcohol evaporates. In wine making, the sugars of grapes are fermented to produce the wine.

Animals and some bacteria and fungi carry out **lactic acid fermentation.** Lactate (lactic acid) is a waste product of this process. Our muscles undergo lactic acid fermentation during strenuous exercise, when oxygen cannot be delivered to the muscles quickly enough. The buildup of lactate is what makes your muscles sore after vigorous exercise. Bacteria that produce lactate are used to make cheese and yogurt (**Figure** 4.14). Tooth decay is also accelerated by lactate from the bacteria that use the sugars in your mouth. In all these types of fermentation, the goal is the same: to recycle NAD^+ for glycolysis.

Figure 4.14: Products of fermentation include cheese (lactic acid fermentation) and wine (alcoholic fermentation). (12)

Lesson Summary

- Cellular respiration is the breakdown of glucose to release energy in the form of ATP.
- Glycolysis, the conversion of glucose into two 3-carbon pyruvate molecules, is the first step of cellular respiration.
- If oxygen is available, the pyruvate enters the mitochondria and goes through a series of reactions, including the citric acid cycle, to produce more ATP.
- If oxygen is not available, the pyruvate is reduced during the process of fermentation to free up more NAD^+ for glycolysis, and there is no net gain of ATP.

Review Questions

1. What are the products of alcoholic fermentation?
2. What is the metabolic process where glucose is ultimately converted to two molecules of pyruvate?
3. Why do your muscles get sore after vigorous exercise?
4. What is the purpose of fermentation?
5. Where does the citric acid cycle take place?
6. Write the chemical reaction for the overall process of cellular respiration.
7. Which is more efficient, aerobic or anaerobic cellular respiration?
8. What are the important electron-accepting enzymes in cellular respiration?
9. What is chemiosmosis?

Further Reading / Supplemental Links

- http://en.wikipedia.org/wiki/Cellular_respiration
- http://biology.clc.uc.edu/Courses/bio104/cellresp.htm
- http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookGlyc.html
- http://biology.clc.uc.edu/Courses/bio104/cellresp.htm
- http://www.science.smith.edu/departments/Biology/Bio231/glycolysis.html

Vocabulary

aerobic respiration Cellular respiration in the presence of oxygen.

alcoholic fermentation Fermentation in the absence of oxygen; produces ethyl alcohol (drinking alcohol) and carbon dioxide; occurs in yeasts.

anaerobic respiration Cellular respiration in the absence of oxygen; fermentation.

ATP A usable form of energy inside the cell; adenosine triphosphate.

cellular respiration The process in which the energy in food is converted into energy that can be used by the body's cells; in other words, glucose (and oxygen) is converted into ATP (and carbon dioxide and water).

citric acid cycle Middle phase of cellular respiration; formation of electron carriers occurs during this phase; also known as the Kreb's cycle.

cristae The inner membrane of the mitochondria. The inner membrane of the mitochondria.

electron transport chain Last phase of cellular respiration; used to power the formation of ATP occurs during this phase.

$FADH_2$ Electron carrier produced during the Kreb's cycle.

fermentation Anaerobic respiration in which NAD^+ is recycled so that is can be reused in the glycolysis process.

glycolysis First phase of cellular respiration; breakdown of glucose occurs during glycolysis; produces two 3-carbon pyruvate molecules.

lactic acid fermentation Anaerobic respiration that recycles NAD^+ for glycolysis; occurs in animals and some bacteria and fungi.

matrix The inner compartment of the mitochondrion that is filled with enzymes in a gel-like fluid.

mitochondria Organelle where cellular respiration occurs; known as the "powerhouse" of the cell because this is the organelle where the ATP that powers the cell is produced.

NADH Electron carrier produced during glycolysis and the citric acid cycle.

Points to Consider

- Now that we know how the cell gets its energy, we are going to turn our attention to cell division. Cell division is a highly regulated process.
- What do you think could happen if your cells divide uncontrollably?
- When new life is formed, do you think it receives all the DNA of the mother and the father?
- Why do you think you might need new cells throughout your life?

Image Sources

(1) http://en.wikipedia.org/wiki/Image:Osmotic_pressure_on_blood_cells_diagram.svg. Public Domain.

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(11) http://commons.wikimedia.org/wiki/Image:Scheme_facilitated_diffusion_in_cell_membrane-en.svg. Public Domain.

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Chapter 5

Cell Division, Reproduction, and DNA

5.1 Lesson 5.1: Cell Division

Lesson Objectives

- Explain why cells need to divide.
- List the stages of the cell cycle and explain what happens at each stage.
- List the stages of mitosis and explain what happens at each stage.

Check Your Understanding

- What is the cell theory?
- In what part of your cells is the genetic information located?

Introduction

Imagine the first stages of a life. In humans, a sperm fertilizes an egg, forming the first cell. From that one cell, an entire baby with trillions of cells will develop. How does a new life go from one cell to so many? The cell divides in half, creating two cells. Then those two cells divide. The new cells continue to divide and divide. One cell becomes two, then four, then eight, and so on (**Figure** 5.1). Rapid cell division allows the development of new life, but cell division must be tightly regulated. If the body's close regulation of cell division is disrupted later in life, diseases such as cancer can develop. Cancer involves cells that divide in an uncontrolled manner. Therefore, much research into cell division is underway across the globe in effort to further understand this process and find a cure for cancer.

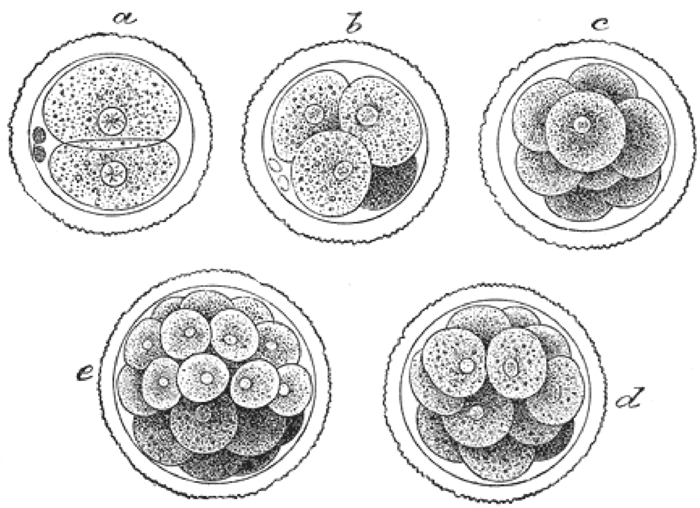

Figure 5.1: Cells divide repeatedly to produce an embryo. Previously the one-celled zygote divided to make two cells (a). Each of the two cells divides to yield four cells (b), then the four cells divide to make eight cells(c), and so on. Through cell division, an entire embryo forms from one initial cell. (17)

Why Cells Divide

Besides the development of a fetus, there are many other reasons that cell division is necessary to life. To grow and develop, you must form new cells. Imagine how often your cells must divide during a growth spurt. Growing just an inch requires countless cell divisions.

Another reason for cell division is to repair damaged cells. Imagine you cut your finger. After the scab forms, it will eventually disappear and new skin cells will grow to repair the wound. Where do these cells come from? Remember that according to the cell theory, all cells must come from preexisting cells. In order to make new skin cells, some of your existing skin cells had to undergo cell division.

Besides suffering physical damage, your cells can simply wear out. Over time you must replace old and worn-out cells. Again, cell division is essential to this process. You can only make new cells by dividing similar preexisting cells.

The Cell Cycle

The process of cell division in eukaryotic cells is carefully regulated. The **cell cycle** which in essence is the lifecycle of a cell, is composed of a series of steps that lead to cell division (**Figure** 5.2). These steps can be divided into two main components: interphase and mitosis.

Interphase is when the cell mainly performs its "everyday" functions; for example, it is when a kidney cell does what a kidney cell is supposed to do. On the other hand, mitosis is when the cell prepares to become two cells. Some cells, like nerve cells, do not complete the cell cycle and divide, while others divide repeatedly.

Most of the cell cycle consists of **interphase,** the time between cell divisions. During this time the cell carries out its normal functions and prepares for the next stage. Interphase can be divided into three stages: the first growth phase (G1), the synthesis phase (S), and the second growth phase (G2). During the G1 stage, the cell doubles in size and doubles the number of organelles. Next, during the S stage, the DNA is replicated. In other words, an identical copy of all the cell's DNA is made. This ensures that each new cell that results after cell division has a set of genetic material identical to that of the parental cell. DNA replication will be further discussed in lesson 3. Finally, in the G2 stage proteins are synthesized that will aid in cell division. In the end of interphase, the cell is ready to enter the mitotic phase.

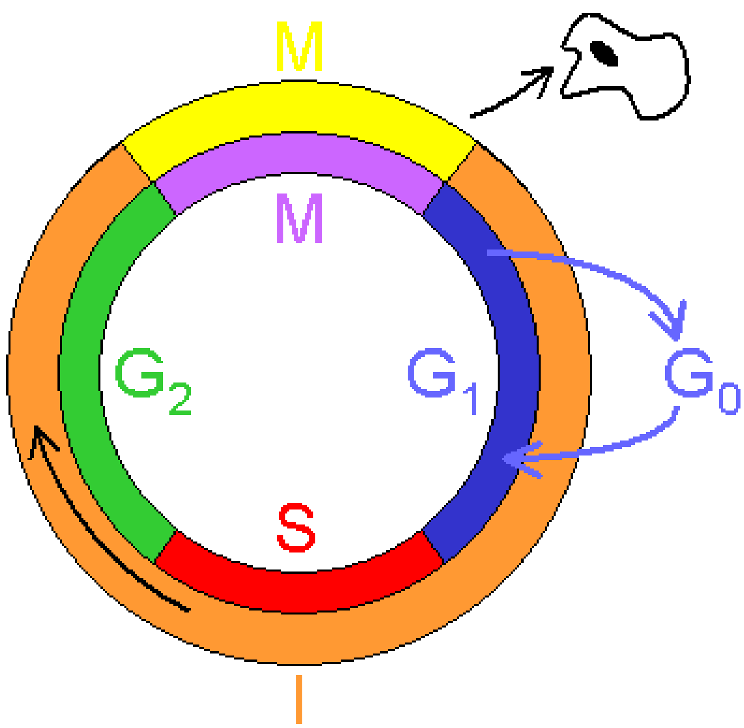

Figure 5.2: The cell cycle is the repeated process of growth and division. Notice that most of the cell cycle is spent in interphase (G1, S, and G2) (I). (2)

During the mitotic phase, nuclear division occurs, which is known as **mitosis**. Also **cytokinesis**, the division of the cytoplasm, occurs. After cytokinesis, cell division is complete and two genetically identical daughter cells have been produced from one parent cell. The term "genetically identical" refers to the fact that each resulting cell has an identical set of DNA, and this DNA is also identical to that of the parent cell.

Mitosis and Chromosomes

During cell division, two nuclei must form during the process of mitosis, so that one nucleus can be given to each of cells that form from cytokinesis. In the nucleus, the genetic information of the cell, DNA, is stored. The copied DNA needs to be moved into a new nucleus for the new cell to have a correct set of genetic instructions.

The DNA in the nucleus is condensed into **chromosomes**, structures composed of DNA wrapped around proteins. Each organism has a unique number of chromosomes; in human cells our DNA is divided up into 23 pairs of chromosomes. When a cell is not undergoing division, such as during interphase, the complex of DNA and proteins is a tangled mass of threads known as chromatin. As mitosis begins, however, the DNA becomes tightly coiled into the chromosomes which become visible under a microscope.

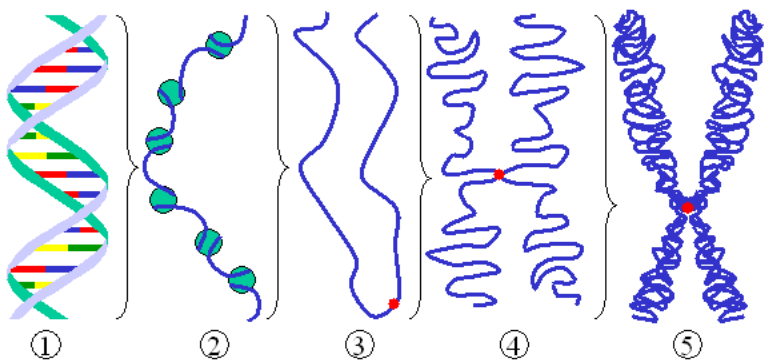

Figure 5.3: The DNA double helix wraps around histone proteins (2) and tightly coils a number of times to form a condensed chromosome (5). The chromosomes contains millions of nucleotide bases. This figure illustrates the complexity of the coiling process. The red dot shows the location of the centromere, where the microtubules attach during mitosis and meiosis. (16)

As mentioned previously, the DNA is replicated during the S stage of interphase. Each chromosome now has two identical molecules of DNA, called sister **chromatids,** forming the "X" shaped molecule depicted in **Figure** 5.3. During mitosis, the two sister chromatids must be split apart to give rise to two identical chromosomes (in essence, each resulting chromosome is made of 1/2 of the "X"). Through this process, each daughter cell receives one copy of each chromosome.

Mitosis is divided into four phases: prophase, metaphase, anaphase, and telophase. During prophase, the chromosomes become tightly wound and become visible under the microscope. Also, the nuclear envelop dissolves, and the spindle begins to form. The **spindle** is a structure containing many fibers that helps to move the chromosomes. By late prophase, the chromosomes are attached to the spindle fibers. The spindle fibers will later pull the chromosomes into alignment.

During metaphase, the chromosomes line up across the center of the cell. The chromosomes line up in a row, one on top of the next. During anaphase, the two sister chromatids of each chromosome separate, resulting in two sets of identical chromosomes. During telophase, the spindle dissolves and nuclear envelopes form around the chromosomes. The drawings of **Figure** 5.4 show this process. This is further shown in **Figure** 5.5. Each new nucleus contains the exact same number and types of chromosomes as the original cell. The cell is now ready for cytokinesis, producing two genetically identical cells, each with its own nucleus.

Lesson Summary

- Cells divide for growth, development, reproduction and replacement of injured or worn-out cells.
- The cell cycle is a serious of regulated steps by which a cell divides.
- During mitosis, the newly duplicated chromosomes are divided into two daughter nuclei.

Review Questions

1. In what phase of mitosis are chromosomes moving toward opposite sides of the cell?
2. In what phase of mitosis do the duplicated chromosomes condense?
3. What step of the cell cycle is the longest?
4. What is the term for the division of the cytoplasm?
5. What happens during the S stage of interphase?
6. Interphase used to be considered the "resting" stage of the cell cycle. Why is this not correct?
7. What are some reasons that cells divide?
8. During what stage of the cell cycle does the cell double in size?
9. Why must cell division be tightly regulated?
10. What is the purpose of mitosis?

Further Reading / Supplemental Links

- http://en.wikipedia.org/wiki/Mitosis
- http://www.biology.arizona.edu/Cell_bio/tutorials/cell_cycle/cells3.html
- http://biology.clc.uc.edu/courses/bio104/mitosis.htm
- http://en.wikipedia.org/wiki/Cell_cycle
- http://www.cellsalive.com/mitosis.htm

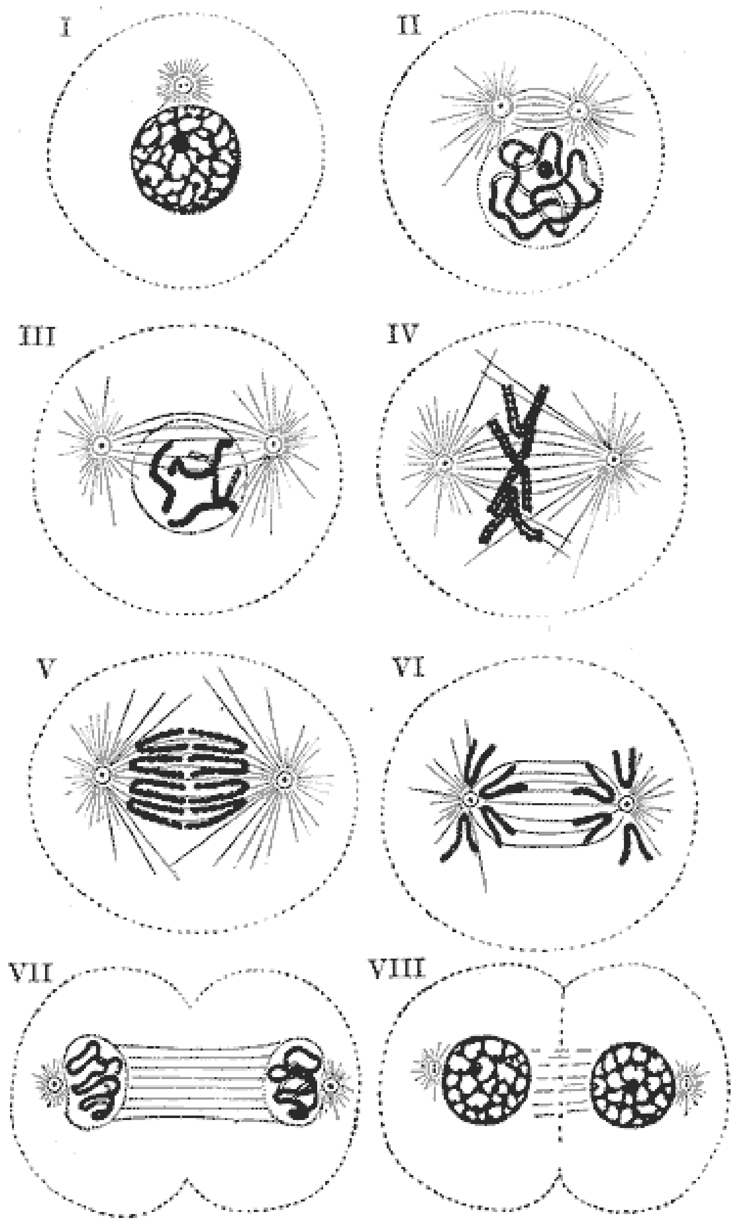

Figure 5.4: An overview of mitosis: during prophase (I and II) the chromosomes condense, during metaphase the chromosomes line up (III and IV), during anaphase the sister chromatids are pulled to opposite sides of the cell (V and VI), during telophase the nuclear envelope forms (and VII and VIII). (14)

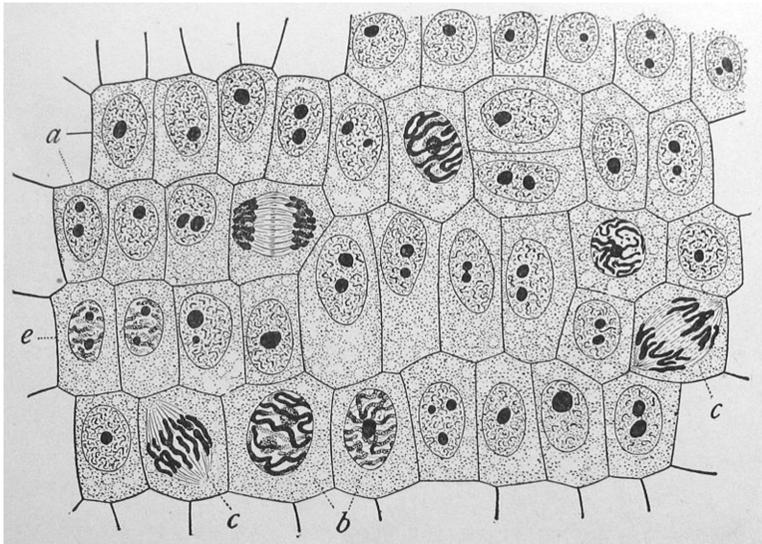

Figure 5.5: This is a picture of dividing plant cells. Cell division in plant cells differs slightly from animal cells as a cell wall must form. Note that most of the cells are in interphase. Can you find examples of the different stages of mitosis? (7)

- http://www.wisc-online.com/objects/index_tj.asp?objID=AP13604

Vocabulary

anaphase Third phase of mitosis where sister chromatids separate and move to opposite sides of the cell.

cell cycle Sequence of steps in eukaryotic cells that leads to cell division.

chromatin Complex of DNA and proteins that is visible when a cell is not dividing.

chromosomes DNA wound around proteins; forms during prophase of mitosis and meiosis.

cytokinesis Division of the cytoplasm after mitosis or meiosis.

interphase Stage of the cell cycle when DNA is synthesized and the cell grows; composed of the first three phases of the cell cycle.

metaphase Second phase of meiosis where the chromosomes are aligned in the center of the cell.

mitosis Sequence of steps in which a nucleus is divided into two daughter nuclei, each with an identical set of chromosomes.

prophase Initial phase of mitosis where chromosomes condense, the nuclear envelope dissolves and the spindle begins to form.

spindle Fibers that move chromosomes during mitosis and meiosis.

telophase Final phase of mitosis where a nuclear envelop forms around each of the two sets of chromosomes.

Points to Consider

- How might a cell without a nucleus divide?
- How are new cells made that incorporate the DNA of two parents?

5.2 Lesson 5.2: Reproduction

Lesson Objectives

- Name the types of asexual reproduction.
- Explain the advantage of sexual reproduction.
- List the stages of meiosis and explain what happens in each stage.

Check Your Understanding

- Can something that does not reproduce still be considered living?
- What stores the genetic information that is passed on to offspring?
- How many chromosomes are in the human nucleus?

Introduction

Can an organism be considered alive if it cannot make the next generation? For a species to survive, **reproduction,** the ability to make the next generation, is absolutely necessary. For a species to be successful, it not only needs to be well adapted to its environment, but also needs to be successful at reproduction. Reproduction allows a population of organisms to pass on their genetic information to the next generation. There are many different ways that organisms reproduce, and these methods are categorized as either sexual or asexual reproduction. There are advantages and disadvantages to each method, but the result is always the same: a new life begins.

Asexual Reproduction

Some organisms can reproduce **asexually,** meaning that the offspring have a single parent and share the exact same genetic material as the parent. The advantage of asexual reproduction is that it can be very quick and does not require the meeting of two individuals of the opposite sexes. The disadvantage of asexual reproduction is that it does not involve genetic recombination, a process that can result in an adaptive new set of traits. For example, you might inherit one advantageous trait from your maternal grandmother, another adaptive trait from your paternal grandmother, and other adaptive traits from your paternal grandfather. You have the benefit of the many genes from two lineages combining in a new way. An organism that is born through asexual reproduction, however, only has the DNA from one parent, and it is the exact copy of that parent. Therefore, no new combinations of traits can happen.

Prokaryotic organisms, which as you might recall are single-celled, reproduce asexually. Bacteria reproduce through **binary fission,** where they basically divide in half (**Figure** 5.6). First, their chromosome replicates and the cell enlarges. After cell division, the two new cells each have one identical chromosome. Mitosis is not necessary as there is no nucleus. Then new membranes form to separate the two cells. This simple process is beneficial to the bacteria, allowing very rapid reproduction.

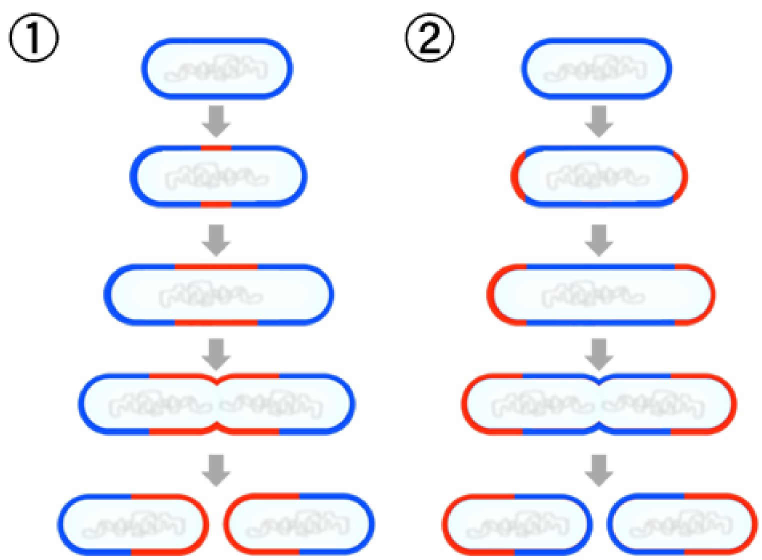

Figure 5.6: Bacteria reproduce by binary fission. Shown is one bacterium reproducing and becoming two bacteria. (1)

There are also several animals that can reproduce asexually. Flatworms can divide in two, then each half regenerates into a new flatworm identical to the original. Many types of insects, fish, and lizards (**Figure** 5.7)can reproduce asexually through parthenogenesis.

Parthenogenesis is a process by which an unfertilized egg cell grows into a new organism. The resulting organism has half the amount of genetic material of the parent, as the starting egg cell has half the amount of DNA compared to the parent. Parthenogenesis is common in honeybees. The fertilized eggs in a hive become workers, while the unfertilized eggs become drones.

Egg cells (and also sperm cells) are produced through a cell division mechanism in which the amount of DNA is halved. This process is called meiosis and will be discussed shortly.

Figure 5.7: This Komodo dragon was born by parthenogenesis. (5)

Sexual Reproduction

During sexual reproduction, two parents are involved. Most animals are dioecious, meaning there is a separate male and female sex, with the male producing sperm and the female producing eggs. When a sperm and egg meet, a **zygote,** the first cell of a new organism, is formed (**Figure** 5.8). The zygote will divide and grow into the embryo.

Animals often have **gonads,** specialized organs that produce eggs or sperm. The male gonads are the **testes,** which produce the sperm, and the female gonads are the **ovaries,** which produce the eggs. Sperm and egg, the two sex cells, are known as **gametes**, and unite through a variety of methods. Fish and other aquatic animals release their gametes in the water, which is called **external fertilization** (**Figure** 5.9). Animals that live on land, however, usually practice **internal fertilization**. Typically males have a penis that deposits sperm into the vagina of the female. Other anatomical features can accomplish the same goal; birds, for example, have a chamber called the cloaca that they place close to another

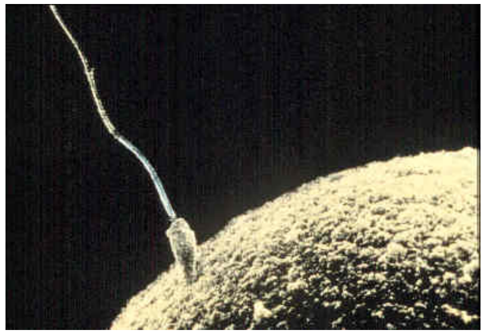

Figure 5.8: During sexual reproduction, a sperm fertilizes an egg. (4)

bird's cloaca to deposit sperm. Whatever method of fertilization is used, the net result is the same: a zygote that contains DNA from both the male and female.

Figure 5.9: This fish guards her eggs, which will be fertilized externally. (15)

Plants also can reproduce sexually, but their reproductive organs are somewhat different than animals' gonads. Most plants are flowering plants, meaning their reproductive parts are contained in a flower. The sperm is contained in the pollen, while the egg is contained in the ovary deep within the flower. The sperm can reach the egg through several methods. In self-pollination, the egg is fertilized by the pollen of same flower. In **cross-pollination**, the sperm from the pollen from one flower fertilizes the egg of another flower. Cross-pollination increases the genetic diversity of the population. Like other types of sexual reproduction, cross-pollination allows new combinations of traits. Cross-pollination can be achieved when pollen is carried by the wind to another flower, or many flowers rely on animal pollinators, like honeybees, or butterflies (**Figure** 5.10) to carry the pollen from flower to flower.

Figure 5.10: Butterflies receive nectar when they deposit pollen into flowers, resulting in cross-pollination. (8)

Fungi can also reproduce sexually, but instead of female and male sexes, they have (+) and (-) strains. When the filaments of a (+) and (-) fungi meet, the zygote is formed. As with the sexual reproduction in plants and animals, each zygote receives DNA from two parent strains.

Meiosis and Gametes

The formation of gametes, the reproductive cells such as sperm and egg, is necessary for sexual reproduction. As gametes are produced, the number of chromosomes must be reduced to half. In humans, our cells have 23 pairs of chromosomes, and each chromosome within a pair is called a **homologous chromosome.** For each of the 23 chromosome pairs, you received one chromosome from your father and one chromosome from your mother. The homologous chromosomes have the same genes, although there might be alternate forms of each gene, called **alleles**, which vary between the chromosomes. These homologous chromosomes are separated during gamete formation, therefore gametes have only 23 chromosomes, not 23 pairs. This separation of chromosomes is random. The probability or chance that a particular allele will be in a gamete is 1 in 2. The gamete may receive either the paternal allele (inherited from the father) or the maternal allele (inherited from the mother). This random separation of chromosomes (and therefore alleles) occurs for each chromosome, resulting in an widely varied combination of chromosomes in each gamete. With 23 pairs of chromosomes, this results in over 8 million different combinations of chromosomes a gamete.

Haploid vs. Diploid

A cell with two sets of chromosomes is **diploid**, referred to as $2n$, where n is the number of sets of chromosomes. A cell with one set of chromosomes, such as a gamete, is **haploid,** referred to as n. So when a haploid sperm and a haploid egg combine, a diploid zygote will be formed; in essence, when a zygote is formed, half of the DNA in the diploid zygote comes from each parent. The process of cell division that reduces the chromosome number by half is called **meiosis.**

Meiosis

Prior to meiosis, DNA replication occurs, so each chromosome contains two **sister chromatids** that are identical to the original chromosome. Meiosis is divided into two nuclear divisions: meiosis I and meiosis II. Each of these nuclear divisions shares many aspects of mitosis and can be divided into the same phases: prophase, metaphase, anaphase, and telophase; however, between the two divisions, DNA replication does not occur. Through this process, one diploid cell will divide into four haploid cells.

Meiosis I

During meiosis I, the pairs of homologous chromosomes are separated from each other. During prophase I, the homologous chromosomes line up together. During this time, **crossing-over** can occur (**Figure** 5.11), the exchange of DNA between homologous chromosomes. Crossing-over increases the new allele combinations in the gametes. Without crossing-over, the offspring would always inherit all of the many alleles on one of the homologous chromosomes. Because of crossing over, the alleles on the homologous chromosomes can be scrambled to pass on unique combinations of alleles on the chromosome. Also during prophase I, the spindle forms and the chromosomes condense as they coil up tightly. The spindle has the same function as in mitosis.

During metaphase I, the homologous chromosomes line up in pairs in the middle of the cell; that is, both chromosome of a pair will line up together. The maternal chromosomes or paternal chromosomes can each attach to either side of the spindle. The assignment of which side is random, so all the maternal or paternal chromosomes do not end up in one gamete. The gamete will contain some chromosomes from the mother and some chromosomes from the father. Note this is different than during metaphase of mitosis; although chromosomes still line up during mitosis, the sister chromatids are separated, and each cell obtains both the maternal and paternal chromosome of each pair.

During anaphase I, the homologous chromosomes separate. In telophase I, the spindle dissolves, but a new nuclear envelop does not need to form. That's because after a brief resting stage, the nucleus will divide again. No DNA replication happens between meiosis I and

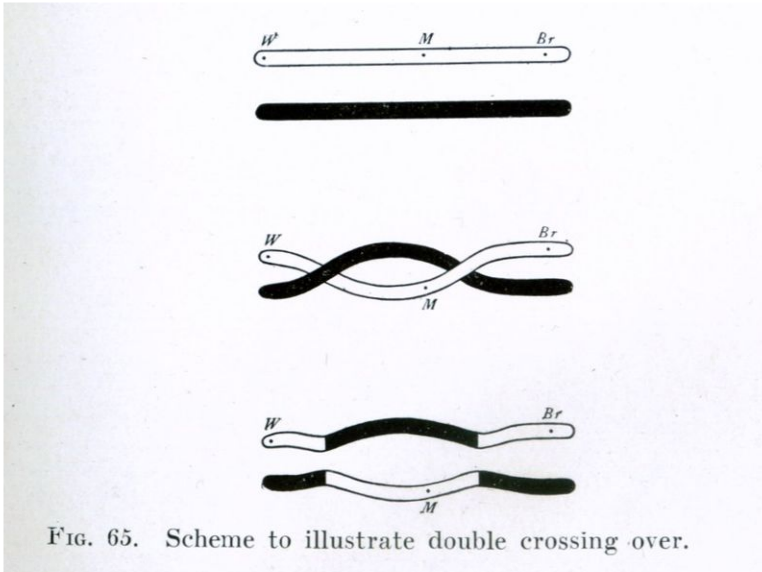

Figure 5.11: During crossing-over, segments of DNA are exchanged between sister chromatids. Notice how this can result in an allele (M) on one sister chromatid being moved onto the other sister chromatid. (19)

meiosis II as the chromosomes are already duplicated, carrying sister chromatids.

Meiosis II

During meiosis II, the sister chromosomes are separated and the gametes are generated. During prophase II, the chromosomes condense. In metaphase II the chromosomes line up one on top of the next along the equator, or middle of the cell. During anaphase II, the sister chromatids separate. After telophase and cytokinesis, each cell has divided again. Therefore, meiosis results in four cells with half the DNA of the parent cell (**Figure** 5.12). In our cells, the parent cell has 46 chromosomes, whereas the cells that result from meiosis have 23 chromosomes. These cells will become gametes. (See **Figure** 5.13).

Lesson Summary

- Organisms can reproduce sexually or asexually.
- The gametes in sexual reproduction must have half the DNA of the parent.
- Meiosis is the process of nuclear division to form gametes.

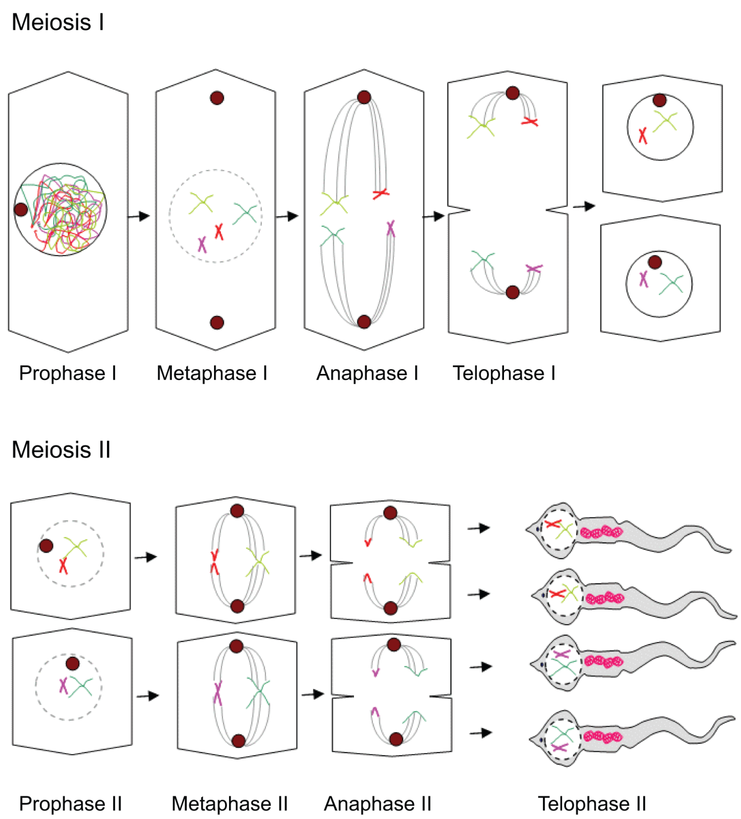

Figure 5.12: An overview of meiosis. (12)

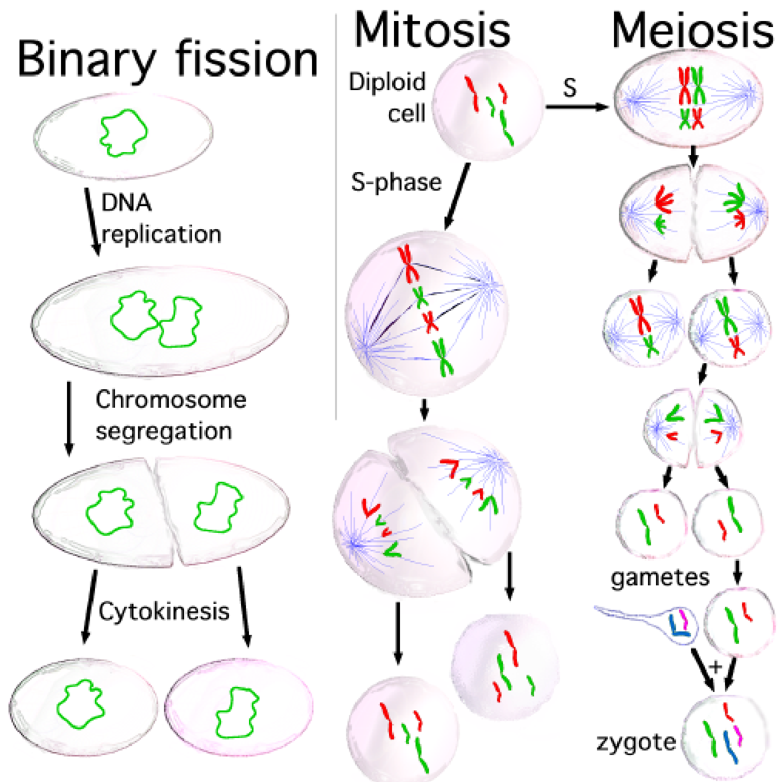

Figure 5.13: A comparison between binary fission, mitosis, and meiosis. (11)

Review Questions

1. What is parthogenesis?
2. How can organisms reproduce asexually?
3. How would sexual reproduction in a lizard be different than a fish?
4. Are the viable eggs that birds lay need to be fertilized externally?
5. How do most plants reproduce sexually?
6. What is the purpose of meiosis?
7. What is the advantage of sexual reproduction over asexual reproduction?
8. If an organism has 12 chromosomes in its cells, how many chromosomes will be in its gametes?
9. During what phase of meiosis do homologous chromosomes separate?
10. In what phase of meiosis do homologous chromosomes pair up?

Further Reading / Supplemental Links

- http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookmeiosis.html
- http://www.biology.arizona.edu/Cell_BIO/tutorials/meiosis/page3.html
- http://www.cellsalive.com/meiosis.htm
- http://www.youtube.com/watch?v=MqaJqLL49a0&NR=1
- http://en.wikipedia.org/

Vocabulary

allele An alternative form of a gene.

asexual reproduction A form of reproduction in which a new individual is created by only one parent.

binary fission An asexual form of reproduction where a cell splits into two daughter cells.

crossing-over Exchange of DNA segments between homologous chromosomes; occurs during prophase I of meiosis.

cross-pollination Sexual reproduction in plants where sperm from the pollen of one flower is received by the ovary of another flower.

diploid When a cell has two sets of chromosomes.

gametes Cells involved in sexual reproduction; typically egg and sperm cells.

gonads Organ that produces gametes, such as the ovaries and testes.

haploid When a cell has only one set of chromosomes, typical of a gamete.

internal fertilization Reproduction occurs through the internal deposit of gametes.

external fertilization Reproduction where the eggs are fertilized outside the body.

meiosis Nuclear division that results in haploid gametes.

ovaries Female gonads in animals that produce eggs.

parthenogenesis Reproduction where an unfertilized egg develops into a new individual.

sexual reproduction Reproduction where gametes from two parents combine to make an individual with an unique set of genes.

sister chromatids Two genetically identical chromosome segments that form after DNA replication.

testes Male gonads in animals that produce sperm.

zygote Single cell that is formed after the fertilization of an egg; the first cell of a new organism.

Points to Consider

- What must be replicated prior to mitosis?
- How do you think DNA might be replicated?
- What might happen if there is a mistake during DNA replication?

5.3 Lesson 5.3: DNA, RNA, and Protein Synthesis

Lesson Objectives

- Explain the chemical composition of DNA.
- Explain how DNA synthesis works.
- Explain how proteins are coded for and synthesized.
- Describe the three types of RNA and the functions of each.

Check Your Understanding

- What is the purpose of DNA?
- When is DNA replicated?

Introduction

Much research in the past fifty years has been focused on understanding the genetic material, DNA. Understanding how DNA works has brought with it many useful technologies. DNA fingerprinting allows police to match a criminal to a crime scene. Transgenic crops, or crops that contain altered DNA, have improved yields for farmers. And you can now test your DNA to find out the chance that your future children may be at risk for a rare genetic disorder. Although we can do some really complicated things with DNA, the chemical structure of DNA is remarkably simple and elegant.

What is DNA?

DNA, is the material that makes up our chromosomes and stores our genetic information. This genetic information is basically a set of instructions that tell your cells what to do. DNA is an abbreviation for deoxyribonucleic acid. As you may recall, nucleic acids are the class of chemical compounds that store information. The *deoxyribo* part of the name refers to the name of the sugar that is contained in DNA, deoxyribose.

The chemical composition of DNA is a polymer, or long chain, of nucleotides. **Nucleotides** are composed of a phosphate group, a 5-carbon sugar, and a nitrogen-containing base. The only difference between each nucleotide is the identity of the base. There are only four possible bases that make up each DNA nucleotide: adenine (A), guanine (G), thymine (T), and cytosine (C). The various sequences of these four bases make up the genetic code of your cells. It may seem strange that there are only four letters in the "alphabet" of DNA. But since your chromosomes contain millions of nucleotides, there are many, many different combinations possible with those four letters.

But how do all these pieces fit together? James Watson and Francis Crick won the Nobel Prize in 1962 for piecing together the structure of DNA. Together with the work of Rosalind Franklin and Maurice Wilkins, they determined that the structure of DNA is two strands of nucleotides in a **double helix** (**Figure** 5.14), or a two-stranded spiral, with the sugar and phosphate groups on the outside, and the paired bases connecting the two strands on the inside of the helix (**Figure** 5.15).

The bases do not pair randomly, however. When Erwin Chargaff looked closely at the base content in DNA, he noticed that the percentage of adenine (A) in the DNA always equaled the percentage of thymine (T), and the percentage of guanine (G) always equaled the percentage of cytosine (C). Watson and Crick's model explained this result by suggesting

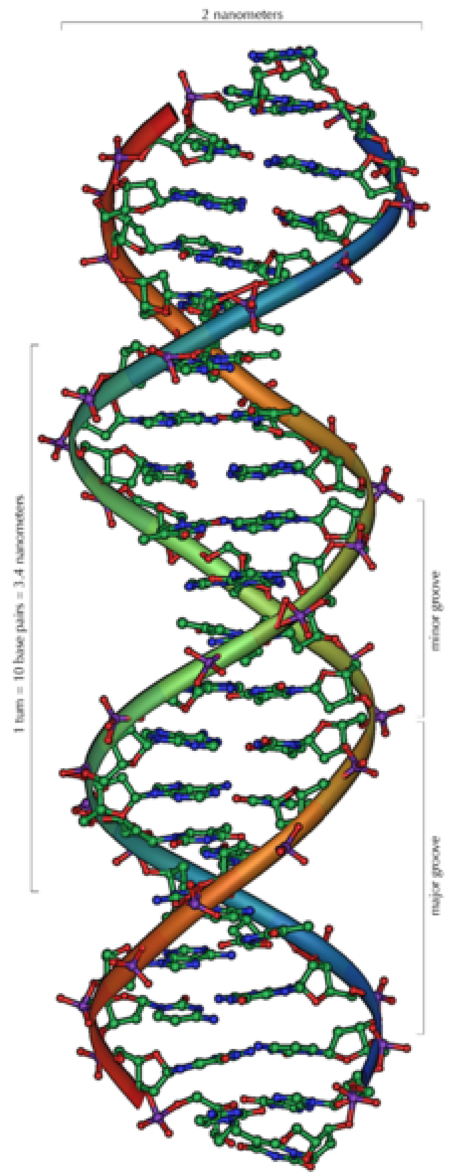

Figure 5.14: DNA's three-dimensional structure is a double helix. The hydrogen bonds between the bases at the center of the helix hold the helix together. (22)

that A always pairs with T and G always pairs with C in the DNA helix. Therefore A and T, and G and C, are complementary bases. If one DNA strand reads ATGCCAGT, the other strand would be made up the complementary bases: TACGGTCA. These base pairing rules state that in DNA, A always pairs with T, and G always pairs with C.

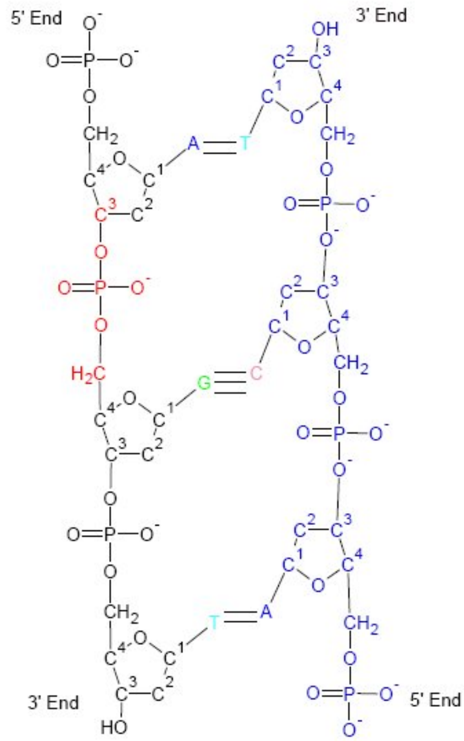

Figure 5.15: The chemical structure of DNA includes a chain of nucleotides consisting of a 5-carbon sugar, a phosphate group, and a nitrogen base. Notice how the sugar and phosphate form the backbone of DNA (one strand in blue), with the hydrogen bonds between the bases joining the two strands. (3)

DNA Replication

The base paring rules are crucial for the process of replication. **DNA replication** is the process by which DNA is copied to form an identical daughter molecule of DNA. During DNA replication, the DNA helix unwinds as the weak hydrogen bonds between the paired bases are broken. The two single strands of DNA then each serve as a template for a new stand to be synthesized. The new nucleotides are placed in the right order because of the base pairing rules. The new set of nucleotides then join together to form a new strand of DNA. The process results in two DNA molecules, each with one old strand and one new strand of DNA. Therefore, this process is known as **semiconservative replication** because one strand is conserved in each new DNA molecule (**Figure** 5.16).

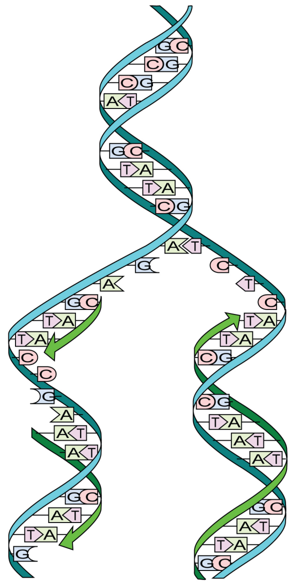

Figure 5.16: DNA replication occurs by the DNA strands "unzipping", and the original strands of DNA serve as a template for new nucleotides to join and form a new strand. (21)

Protein Synthesis

The code of DNA, stored in the base sequences, contains the instructions for the order of assembly of amino acids to make proteins. Each strand of DNA has many, many separate sequences that code for the production of a specific protein. These discrete units of DNA that contain code for the creation of one protein are called **genes.** Proteins are made up of units called **amino acids**, and the sequence of bases in DNA codes for the specific sequence of amino acids in a protein.

There are about 22,000 genes in every human cell. Does every human cell have the same genes? Yes. Does every human cell use the same genes to make the same proteins? No. In a multicellular organism, such as us, cells have specific functions because they have different proteins, and they have different proteins because different genes are expressed in different cell types. Think of **gene expression** as if all your genes usually are "turned off." Each cell type only "turns on" (or expresses) the genes that have the code for the proteins it needs to use. So different cell types "turn on" different genes, allowing different proteins to be made, giving different cell types different functions.

However, DNA does not directly coordinate the production of proteins. Remember that DNA is found in the nucleus of the cell, but proteins are made on the ribosomes in the cytoplasm. How do the instructions in the DNA get out to the cytoplasm so that proteins can be made? DNA sends out a message, in the form of **RNA** (ribonucleic acid), describing how to make the protein. There are three types of RNA directly involved in protein synthesis. Messenger RNA (mRNA) carries the instructions from the nucleus to the cytoplasm. The other two forms of RNA, ribosomal RNA (rRNA) and transfer RNA (tRNA) are involved in the process of ordering the amino acids to make the protein. This process is called translation and will be discussed below. All three RNAs are nucleic acids and are therefore made of nucleotides. The RNA nucleotide is very similar to the DNA nucleotide except for the fact that it contains a different kind of sugar, ribose, and the base uracil (U) replaces the thymine (T) found in DNA.

mRNA is created in a method very similar to DNA synthesis. mRNA is also made up of nucleotide units. The double helix unwinds and the nucleotides follow basically the same base paring rules to form the correct sequence in the mRNA. This time, however, U pairs with each A in the DNA. In this manner, the genetic code is securely passed on to the mRNA. The process of constructing a mRNA molecule from DNA is known as **transcription** (**Figures** 5.17 and 5.18).

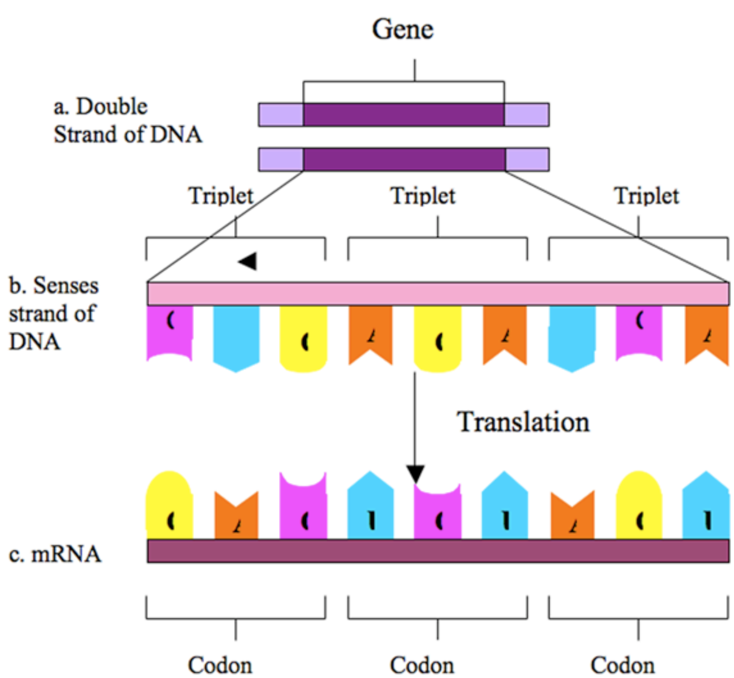

Figure 5.17: Each gene (a) contains triplets of bases (b) that are transcribed into RNA (c). Every triplet, or codon, encodes for a unique amino acid. (20)

The mRNA is directly involved in the protein synthesis process and tells the ribosome (**Figure** 5.19) how to assemble a protein. The base code in the mRNA dictates the order of the amino acids in the protein. But because there are only 4 bases in mRNA and 20 different amino acids, one base cannot directly code for one amino acid. The genetic

Figure 5.18: Base-pairing ensures the accuracy of transcription. Notice how the helix must unwind for transcription to take place. (10)

code in mRNA is read in "words" of three letters (triplets), called **codons.** For example, GGU encodes for the amino acid glycine, while GUC encodes for valine. This genetic code is universal and used by almost all living things. These codons are read in the ribosome, the organelle responsible for protein synthesis. In the ribosome, tRNA reads the code and brings a specific amino acid to attach to the growing chain of amino acids, which is a protein in the process of being synthesized. Each tRNA carries only one type of amino acid and only recognizes one specific codon. The process of reading the mRNA code in the ribosome to synthesize a protein is called **translation** (**Figure** 5.20). There are also three codons, UGA, UAA, and UAG, which indicate that the protein is complete. They do not have an associated amino acid. As no amino acid can be added to the growing polypeptide chain, the protein is complete. The chart in **Figure** 5.21 should be of use in this area of study.

Mutations

The process of DNA replication is not always 100% accurate, and sometimes the wrong base is inserted in the new strand of DNA. A permanent change in the sequence of DNA is known as a **mutation** (**Figure** 5.22).A mutation may have no effect on the phenotype or can cause the protein to be manufactured incorrectly, which can affect how well the protein works, or whether it works at all. Usually the loss of a protein function is detrimental to the organism.

However, in rare circumstances, the mutation can be beneficial. For example, suppose a mutation in an animal's DNA causes the loss of an enzyme that makes a dark pigment in the animal's skin. If the population of animals has moved to a light colored environment, the animals with the mutant gene would have a lighter skin color and be better camouflaged. So in this case, the mutation was beneficial.

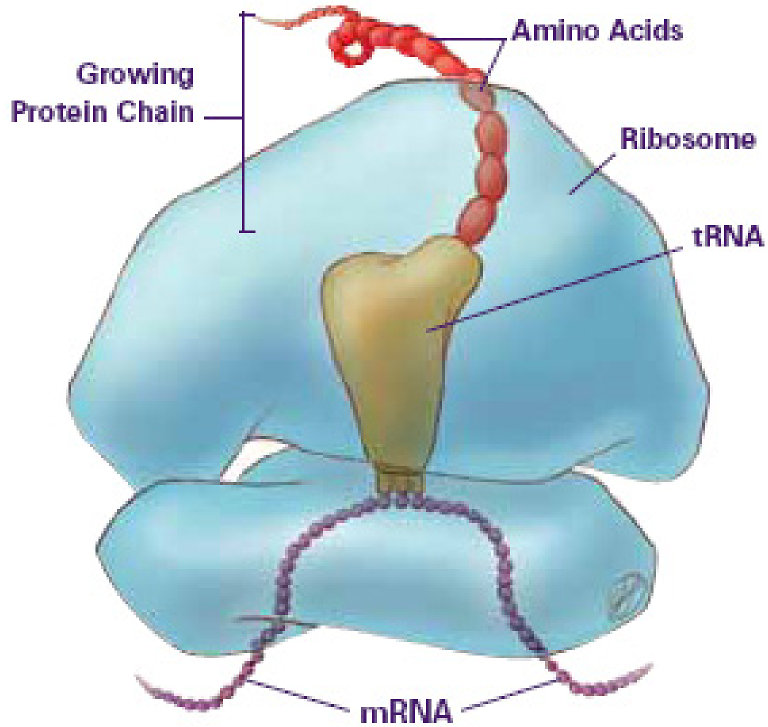

Figure 5.19: Ribosomes translate RNA into a protein with a specific amino acid sequence. The tRNA binds and brings to the ribosome the amino acid encoded by the mRNA. Ribosomes are made of rRNA and proteins. (6)

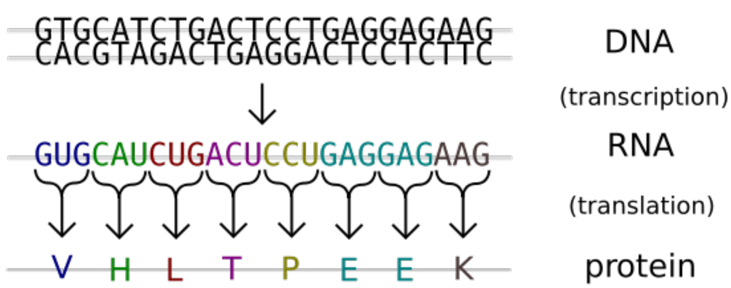

Figure 5.20: This summary of how genes are expressed shows that DNA is transcribed into RNA, which is translated in turn to protein. (13)

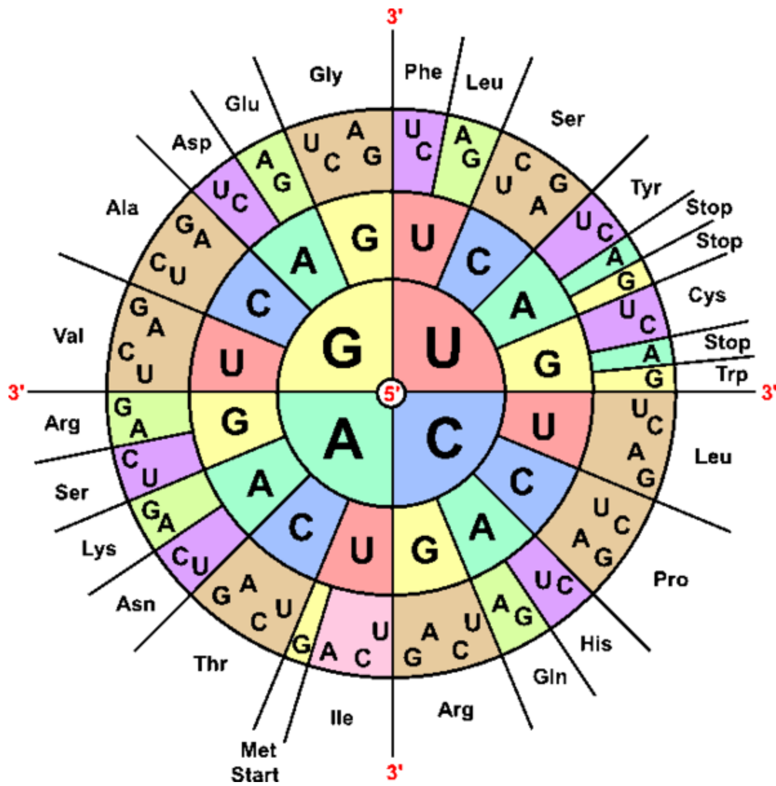

Figure 5.21: This chart shows the genetic code used by all organisms. For example, an RNA codon reading GUU would encode for a valine (Val) according to this chart. Start at the center for the first base of the three base codon, and work your way out. Notice for valine, the second base is a U and the third base of the codon may be either a G, C, A, or U. Similarly, glycine (Gly) is encoded by a GGG, GGA, GGC, and GGU. (9)

There are many possible types of mutations possible in chromosomes. In the case of a point mutation, there is a change in a single nucleotide. Other mutations can be more dramatic. A large segment of DNA can be deleted, duplicated, inverted, or inserted in the wrong place. These mutations usually result in a non-functional protein, or a number of non-functional proteins. A deletion is when a segment of DNA is lost, so there is a missing segment in the chromosome. A duplication is when a segment is repeated, creating a longer chromosome. In an inversion, the segment of DNA is flipped and then reattached to the chromosome. An insertion is when a segment of DNA from one chromosome is added to another, unrelated chromosome.

Even if a single base is changed, it can cause a major problem. The substitution of a single base is called a point mutation. Sickle cell anemia is an example of a condition caused by a point mutation in the hemoglobin gene. In this gene, just the one base change causes a different amino acid to be inserted in the hemoglobin protein, causing the protein to fold differently and not function properly in carrying oxygen in the bloodstream.

If a single base is deleted, it can also have huge effects on the organism because this would cause a frameshift mutation. Remember that the bases are read in groups of three by the tRNA. If the reading frame gets off by one base, the resulting sequence will consist of an entirely different set of codons. The reading of an mRNA is like reading three letter words of a sentence. Imagine you wrote "big dog ate red cat". If you take out the second letter, the frame will be shifted so now it will read "bgd oga ter edc at." One single deletion makes the whole "sentence", or mRNA, not read correctly.

Many mutations are not caused by errors in replication. Mutations can happen spontaneously and they can be caused by **mutagens** in the environment. An example of a mutagen is radiation. High levels of radiation can alter the structure of DNA. Also, some chemicals, such as those found in tobacco smoke, can be mutagens. Sometimes mutagens can also cause cancer. Tobacco smoke, for example, is often linked to lung cancer.

Lesson Summary

- DNA stores the genetic information of the cell in the sequence of its 4 bases: adenine, thymine, guanine, and cytosine.
- The information in a small segment of DNA, a gene, is sent by mRNA to the ribosome to synthesize a protein.
- Within the ribosome, tRNA reads the mRNA in sets of three bases (triplets), called codons, which encode for the specific amino acids that make up the protein.
- A mutation is a permanent change in the sequence of bases in DNA.

Review Questions

1. Translate the following segment of DNA into RNA: AGTTC

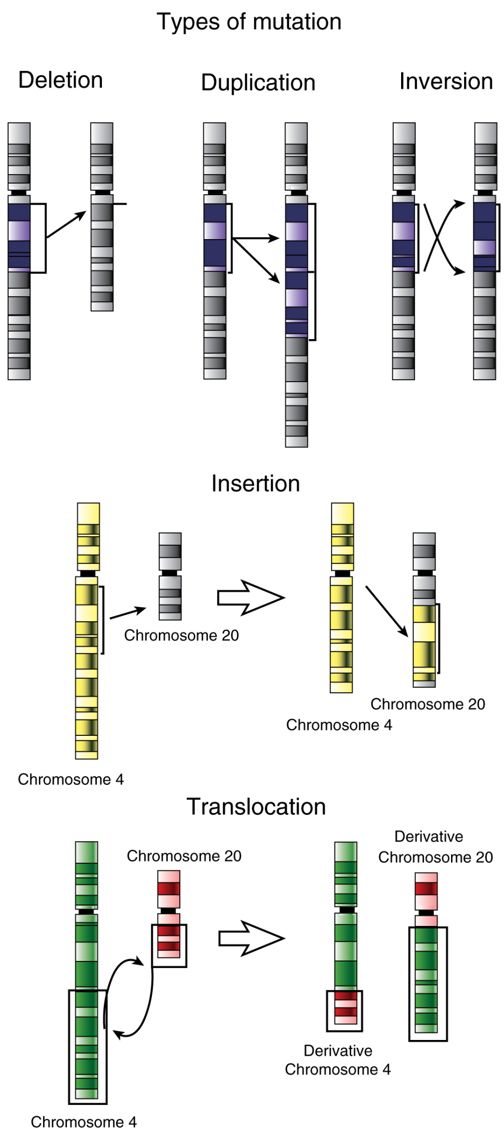

Figure 5.22: Mutations can arise in DNA through deletion, duplication, inversion, insertion, and translocation within the chromosome. A deletion is when a segment of DNA is lost from the chromosome. A duplication is when a segment is repeated. In an inversion, the segment of DNA is flipped and then re-annealed. An insertion or translocation can cause DNA from one chromosome to be added onto another, unrelated chromosome. (18)

2. Write the complimentary DNA nucleotides to this strand of DNA: GGTCCA
3. What makes up a nucleotide?
4. Nucleotides are subunits of which polymers?
5. Amino acids are subunits that make up what polymer?
6. Describe the process of DNA replication
7. Name a mutagen.
8. What is made in the process of transcription?
9. What is made in the process of translation?
10. How does RNA encode for proteins?

Further Reading / Supplemental Links

- http://www.phschool.com/science/biology_place/biocoach/dnarep/intro.html
- http://nobelprize.org/educational_games/medicine/dna_double_helix/readmore.html
- http://www.biostudio.com/demo_freeman_protein_synthesis.htm
- http://learn.genetics.utah.edu/units/basics/transcribe/
- http://www-class.unl.edu/biochem/gp2/m_biology/animation/gene/gene_a2.html
- http://learn.genetics.utah.edu/units/basics/builddna/
- http://enwikipedia.org/
- http://sickle.bwh.harvard.edu/scd_background.html

Vocabulary

amino acid The units (monomers)that combine to make proteins.

DNA Deoxyribonucleic acid; a nucleic acid that is the genetic material of all organisms.

DNA replication The synthesis of new DNA; occurs during the S phase of the cell cycle.

double helix Describes the shape of DNA as a double spiral; similar to a spiral staircase.

gene The inherited unit of DNA that encodes for one protein (or one polypeptide).

mutagen A chemical or physical agent that can cause changes to accumulate in DNA.

mutation A change in the nucleotide sequence of DNA.

nucleotide The units that make up DNA; consists of a 5-carbon sugar, a phosphate group, and a nitrogen-containing base

RNA The nucleic acid that carries the information stored in DNA to the ribosome.

semiconservative replication Describes how the replication of DNA results in two molecules of DNA, each with one original strand and one new strand.

transcription The synthesis of a RNA that carries the information encoded in the DNA.

translation The synthesis of proteins as the ribosome reads each codon in RNA, which code for a specific amino acid.

Points to Consider

- Your cells have "proofreaders" that replace mismatched pairs that occurred during DNA synthesis. How would that affect the rate of mutation in your body?
- There are many diseases due to mutations in the DNA. These are known as genetic diseases, and many can be passed onto the next generation. Think about how a single base change cause a huge medical problem like sickle cell anemia.
- Your DNA contains the instructions to make you. So is everyone's DNA different? Can it be used to distinguish individuals, like a fingerprint?

Image Sources

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Chapter 6

Genetics

6.1 Lesson 6.1: Gregor Mendel and the Foundations of Genetics

Lesson Objectives

- Explain Mendel's law of segregation.
- Draw a Punnett square to make predictions about the traits of the offspring of a simple genetic cross.

Check Your Understanding

- What is the genetic material of our cells?
- How does meiosis affect the chromosome number in gametes?

Introduction

For centuries people have been fascinated with the inheritance of human traits. People might say, "You have your father's eyes." or, "You have red hair like your granddad; it must have skipped a generation." These comments show an appreciation of the laws of human inheritance. We inherit traits from our ancestors, and sometimes traits can stay hidden and show up in later generations. **Genetics,** the study of inheritance, explains how traits are passed on from one generation to the next. Due to recent developments in the field of genetics, we can now seek to understand the inheritance of disease. People today may ask "What are the chances my child will have cystic fibrosis?" and "What is the likelihood that I may have breast cancer if my grandmother had it?" Genetic counselors are trained to address families' questions about the probabilities of passing on a genetic disorder. When genetic counselors sit down with families to discuss these types of questions, it's amazing that their answers are derived from the fundamentals of genetics discovered by a monk in the 1800s.

Figure 6.1: Gregor Mendel (9)

Mendel's Experiments

The laws of heredity were first developed by an Austrian monk, Gregor Mendel (**Figure** 6.1), in the 1800s. To study genetics, Mendel chose to work with pea plants because they had easily observable traits and a short generation time (**Figure** 6.2). For example, pea plants are either tall or short, which are easily identifiable traits. Furthermore, peas can either self pollinate or be cross-pollinated by hand, by transferring the pollen from one flower to the stigma of another. In this way, Mendel could carefully observe the results of crosses between two different types of plants. He studied the inheritance patterns for many different traits in peas, including round seeds versus wrinkled seeds, white flowers versus purple flowers, and tall plants versus short plants. Because of his work, Mendel can be considered the father of genetics.

During Mendel's time, most people believed that traits were contributed from both parents and blended together as they were passed down from generation to generation. For example, if you crossed a short plant and a tall plant, they would expect the offspring to be medium-sized plants. What Mendel observed, however, was that the offspring of this cross (called the **F1 generation,** derived from the Latin term *filius,* meaning sons and daughters) were all tall plants. Based on the blending hypothesis, the result of all tall plants was unexpected.

Next, Mendel let the F1 generation self-pollinate. He then noted that 75% of the result-

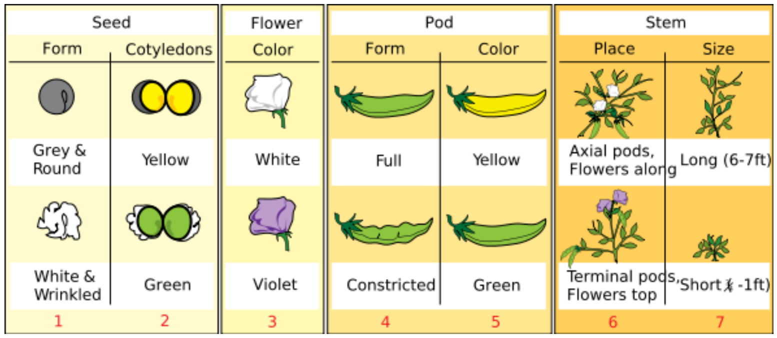

Figure 6.2: Characteristics of pea plants. (11)

ing offspring, the **F2 generation,** were tall, while 25% were short. Therefore, shortness appeared to have skipped a generation. Mendel found this same mathematical result over and over again with all the traits he studied. In all, Mendel studied seven characteristics, with almost 20,000 F2 plants analyzed. For example, purple flowers and white flowers were crossed to produce plants with only purple flowers in the F1 generation. Then after self-pollination, the F2 generation had 75% purple flowers and 25% white flowers. These results did not reflect what you would expect if the blending model of inheritance was correct.

Dominance

Mendel had to come up with a new theory of inheritance to explain his results. His explanation, the **law of segregation**, is still one of the fundamental laws of modern genetics. He proposed that each pea plant had two hereditary factors for each trait. There were two possibilities for each hereditary factor, such as short or tall. One factor is **dominant** to the other, meaning it masks the effects of the **recessive** factor. However, each parent could only pass on one of these factors to the offspring. Therefore, during the formation of **gametes,** sperm or egg, the heredity factors must separate so there is only one factor per gamete. When fertilization occurs, the offspring then have two hereditary factors.

This law explained what Mendel had seen in the F1 generation, because the two heredity factors were the short and tall factors and each individual in the F1 would have one of each factor, and as the tall factor is dominant to the short factor, all the plants appeared tall. In the F2 generation, produced by self-pollination of the F1, 25% of the offspring could have two short heredity factors, so they would appear short. 75% would have at least one tall heredity factor and will be tall.

In genetics problems the dominant factor is labeled with a capital letter (T) while the recessive factor is labeled with a lowercase letter (t). If we designate the letter T or t to represent the heritable factor, as each individual has two factors for each trait, the possible combinations are Tt, TT, and tt. Plants with TT would be tall while plants with tt would be short. Since T is dominant to t, plants that are Tt would be tall, as with the F1 generation we described that inherited one factor from the TT tall parent and one factor from the tt short parent.

Probability and Punnett Squares

To visualize the results of a genetic cross, a **Punnett square** is helpful. An example of a Punnett square (**Figure** 6.3) that shows the results of a cross between two purple flowers that each have one dominant factor and one recessive factor (Bb). Notice how the possible factors in the sperm (B or b) are lined up the side of the square while the possible factors in the egg (B or b) are lined up across the top. The possible offspring are represented by the letters in the boxes, with one factor coming from each parent.

Notice how the Punnett square can help you predict the outcome of the crosses. Only one of the plants out of the four, or 25% of the plants, has white flowers (bb). The other 75% have purple flowers (BB, Bb) because the color purple is a dominant trait in pea plants.

Now imagine you cross one of the white flowers (bb) with a purple flower that has both a dominant and recessive factor (Bb). The only possible gamete in the white flower is the recessive (b), while the purple flower can have gametes with either dominant (B) or recessive (b). If you write out the Punnett cross, you will see that 50% of the offspring will be purple and 50% of the offspring will be white.

Keep in mind that the birth of each offspring is an independent event and has the same probability, so the traits of a previous offspring do not influence the next offspring. In the cross discussed above with two Bb flowers, each offspring has a 75% chance of being purple and a 25% chance of being white. For example, even if the first three offspring in the cross have purple flowers, it does not mean that the next plant must have white flowers. All probability tells you is that overtime the averages of many, many offspring will work out to a predicted ratio.

Table 6.1: **The Punnett Square of a white flower (bb) crossed with a purple flower (Bb)**

	b	b
B	Bb	bb
b	Bb	bb

Lesson Summary

- Gregor Mendel is considered the father of genetics, the science of studying inheritance.
- According to Mendel's law of segregation, an organism has two factors for each trait, but each gamete only contains one of these factors.

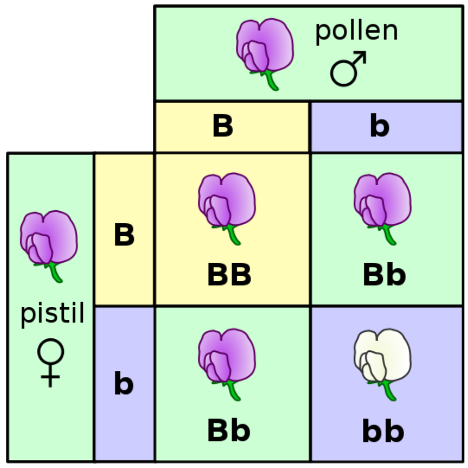

Figure 6.3: The Punnett Square of a cross between two purple flowers (Bb) (18)

- A Punnett square is useful for predicting the outcomes of crosses.

Review Questions

1. What is the term for the offspring of a cross, or the first generation?
2. What is the F2 generation?
3. Who is considered the father of genetics?
4. Why did Mendel select peas as a model for studying genetics?
5. In peas, yellow seeds (Y) are dominant over green seeds (y). If a yy plant is crossed with a YY plant, what ratio of plants in the offspring would you predict?
6. In peas, purple flowers (P) are dominant over white flowers (p). If a pp plant is crossed with a Pp plant, what ratio of plants in the offspring would you predict?
7. In guinea pigs, black fur (B) is dominant over white fur (b). If a BB guinea pig is crossed with a Bb guinea pig, what ratio of guinea pigs in the offspring would you predict?
8. In guinea pigs, smooth coat (S) is dominant over rough coat (s). If a SS guinea pig is crossed with a ss guinea pig, what ratio of guinea pigs in the offspring would you predict?
9. In humans, unattached ear lobes are dominant over attached ear lobes. If two parents have attached earlobes, what is the predicted ratio in the offspring?
10. Why would it be much easier to study genetics in pea plants than in people?

Further Reading / Supplemental Links

- http://www.mendelweb.org/MWtoc.html

- http://www.estrellamountain.edu/faculty/farabee/BIOBK/BioBookgenintro.html
- http://sonic.net/~nbs/projects/anthro201/
- http://anthro.palomar.edu/mendel/mendel_1.htm

Vocabulary

dominant Masks the expression of the recessive trait.

F1 generation The first filial generation; offspring of the P or parental generation.

F2 generation The second filial generation; offspring from the self-pollination of the F1 generation.

gametes Haploid cells involved in sexual reproduction, such egg and sperm.

genetics The study of inheritance.

punnett square Visual representation of a genetic cross that helps predict the expected ratios in the offspring.

recessive Expression is masked by the dominant factor (allele); only expressed if both factors are recessive.

Points to Consider

- Do you think all traits follow this simple pattern where one factor controls the trait?
- Can you think of other examples where Mendel's law does not seem to fit?

6.2 Lesson 6.2: Modern Genetics

Lesson Objectives

- Explain Mendel's laws with our modern understanding of chromosomes.
- Explain how codominant traits are inherited.
- Distinguish between phenotype and genotype.
- Explain how polygenic traits are inherited.

Check Your Understanding

- What is a visual representation of a genetic cross?
- What is stated in Mendel's law of segregation?

Introduction

Although Mendel laid the foundation for modern genetics, there were still a lot of questions left unanswered. How is inheritance determined for traits that do not seem to follow a simple dominant-recessive pattern? What exactly are the hereditary factors that determine traits in organisms? And how do these factors work? One of the great achievements of this past century was the discovery of DNA as the genetic material. And it is the DNA that makes up the hereditary factors that Mendel identified. By applying our modern knowledge of DNA and chromosomes, we can explain Mendel's findings and build on them.

Traits, Genes, and Alleles

Interpreting Mendel's discoveries through the eye of modern genetics, we now know that Mendel's hereditary factors are made up of DNA. Recall that our DNA is wound into chromosomes. Each of our chromosomes contains a long chain of DNA that encodes hundreds, if not thousands, of genes. Each of these genes can have slightly different versions from individual to individual. These variants of genes are called **alleles.** For example, remember that for the height gene in pea plants there are two possible alleles, the dominant allele for tallness (T) and the recessive allele for shortness (t).

Genotype and Phenotype

Genotype refers to the combination of alleles that an individual has for a certain gene. For each gene, an organism has two alleles, one on each chromosome of a homologous pair of chromosomes. The genotype is often referred to with the letter combinations that were introduced in the previous lesson, such as TT, Tt, and tt. When an organism has two of the same alleles for a specific gene, it is **homozygous** for that gene. An organism can be either homozygous dominant (TT) or homozygous recessive (tt). If an organism has two different alleles (Tt) for a certain gene, it is known as **heterozygous.** Genes have a specific place on a specific chromosome, so in the heterozygous individual these alleles are in the same location on each homologous chromosome.

Phenotype refers to the visible traits or appearance of the organism, as determined by the genotype. For example, the phenotypes of Mendel's pea plants were either tall or short, or were purple-flowered or white-flowered. Keep in mind that plants with different genotypes can have the same phenotype. For example, both a pea plant that is homozygous dominant for the tall trait (TT) and heterozygous plant (Tt) would have the phenotype of being tall plants. The recessive phenotype only occurs if the dominant allele is absent, which is when an individual is homozygous recessive (tt).

Incomplete Dominance and Codominance

In all of Mendel's experiments, he worked with traits where a single gene controlled the trait and where one allele was always dominant to the other. Although the rules that Mendel derived from his experiments explain many inheritance patterns, the rules do not explain them all. There are in fact exceptions to Mendel's rules, and these exceptions usually have something to do with the dominant allele.

One exception to Mendel's rules is that one allele is always completely dominant over a recessive allele. Sometimes an individual has an intermediate phenotype between the two parents, as there is no dominant allele. This pattern of inheritance is called **incomplete dominance.**

An example of incomplete dominance is the color of snapdragon flowers. One of the genes for flower color in snapdragons has two alleles, one for red flowers and one for white flowers. A plant that is homozygous for the red allele will have red flowers, while a plant that is homozygous for the white allele will have white flowers. On the other hand, the heterozygote will have pink flowers (**Figure** 6.4). Neither the red nor the white allele is dominant, so the phenotype of the offspring is a blend of the two parents.

Figure 6.4: Pink snapdragons are an example of incomplete dominance. (15)

Another example of incomplete dominance is sickle cell anemia, a disease in which the hemoglobin protein is produced incorrectly and the red blood cells have a sickle shape. A person that is homozygous recessive for the sickle cell trait will have red blood cells that all have the incorrect hemoglobin. A person who is homozygous dominant will have normal red blood cells. And because this trait has an incomplete dominance pattern of expression, a person who is heterozygous for the sickle cell trait will have some misshapen cells and some normal cells (**Figures** 6.5 and 6.6). These heterozygous individuals have a *fitness* advantage; they are resistant to severe malaria. Both the dominant and recessive alleles are expressed, so the result is a phenotype that is a combination of the recessive and dominant traits.

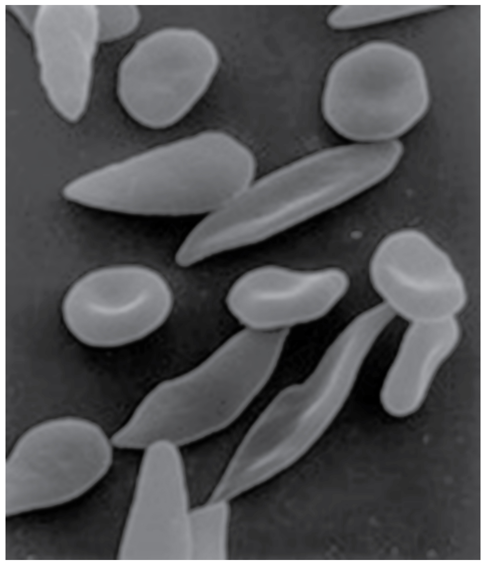

Figure 6.5: Sickle cell anemia causes red blood cells to become misshapen and curved (upper figure) unlike normal, rounded red blood cells (lower figure). (12)

An example of a **codominant** trait is ABO blood types (**Figure** 6.7), named for the carbohydrate attachment on the outside of the blood cell. In this case, two alleles are dominant and completely expressed (designated I^A and I^B), while one allele is recessive (*i*). The I^A allele encodes for red blood cells with the A antigen, while the I^B allele encodes for red blood cells with the B antigen. The recessive allele (*i*) doesn't encode for any antigens. An antigen is a substance that provokes an immune response, your body's defenses against disease, which will be discussed further in the *Diseases and the Body's Defenses* chapter. Therefore a person with two recessive alleles (*ii*) has type O blood. As no dominant (I^A and I^B) allele is present, the person cannot have type A or type B blood.

There are two possible genotypes for type A blood, homozygous (I^AI^A) and heterozygous (I^Ai), and two possible genotypes for type B blood (I^Bi and I^BI^B). If a person is heterozygous for both the I^A and I^B alleles, they will express both and have type AB blood with both antigens on each red blood cell. This pattern of inheritance is significantly different than Mendel's rules for inheritance because both alleles are expressed completely and one does not mask the other.

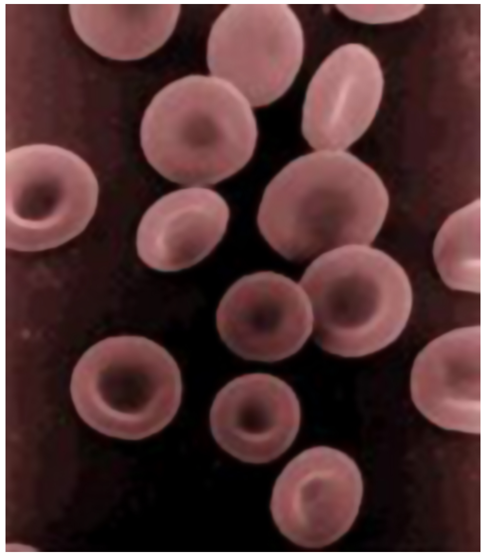

Figure 6.6: Sickle cell anemia causes red blood cells to become misshapen and curved (upper figure) unlike normal, rounded red blood cells (lower figure). (6)

Polygenic Traits and Environmental Influences

Another exception to Mendel's rules is **polygenic inheritance,** which is when a trait is controlled by more than one gene. Often these traits are in fact controlled by many genes on many chromosomes. Each dominant allele has an additive effect, so the resulting offspring can have a variety of genotypes, from no dominant alleles to several dominant alleles. In humans, some examples of polygenic traits are height and skin color. People are neither short nor tall, as was seen with the pea plants studied by Mendel, which has only one gene that encodes for height. Instead, people have a range of heights determined by many genes. Similarly, people have a wide range of skin colors. Polygenic inheritance often results in a bell shaped curve when you analyze the population (**Figure** 6.8). That means that most people are intermediate in the phenotype, such as average height, while very few people are at the extremes, such as very tall or very short.

Most polygenetic traits are partially influenced by the environment. For example, height is partially influenced by nutrition in childhood. If a child is genetically programmed to be average height but does not get a proper diet, he or she may be below average in size.

Other examples of environmentally influenced traits are mental illnesses like schizophrenia and depression. A person may be genetically predisposed to have depression, so when that person's environment contributes major stresses like losing a job or losing a close relative, the person is more likely to become depressed.

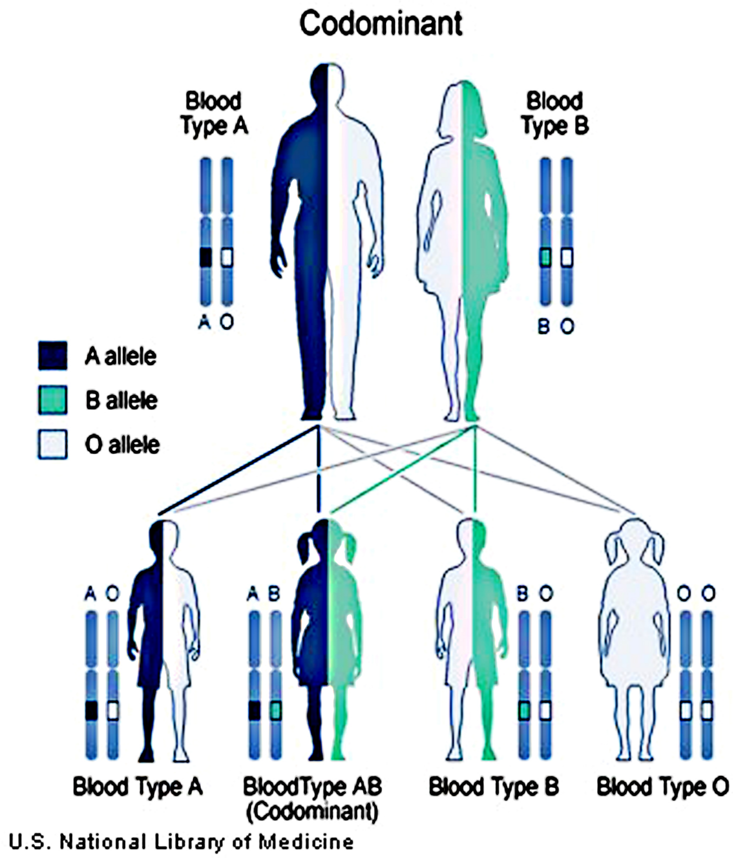

Figure 6.7: An example of codominant inheritance is ABO blood types. (4)

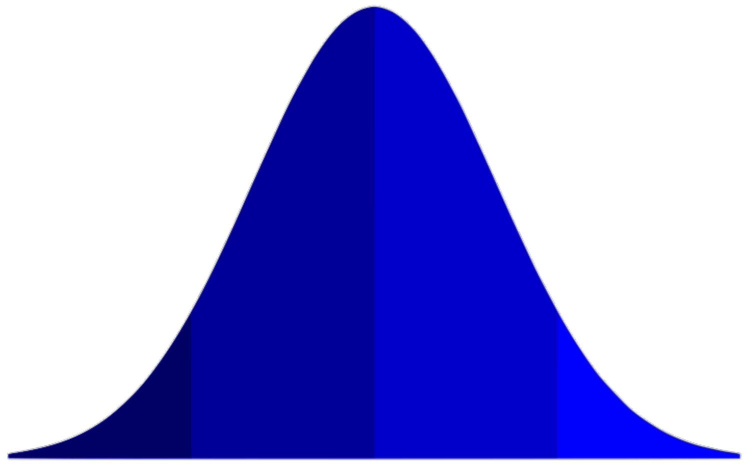

Figure 6.8: Polygenic traits tend to result in a distribution that resembles a bell-shaped curve, with few at the extremes and most in the middle. There may be 4 or 6 or more alleles involved in the phenotype. At the left extreme, individuals are completely dominant for all alleles, and at the other extreme, individuals are completely recessive for all alleles. Individuals in the middle have various combinations of recessive and dominant alleles. (7)

Linkage

Linkage refers to particular genetic position or **loci**, or alleles inherited together, suggesting that they are physically on the same chromosome, and located close together on that chromosome. A crossing-over event during prophase I of meiosis is rare between linked loci. 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.

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 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 farther apart linked genes were on a chromosome, 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 occurred - 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.

Lesson Summary

- Variants of genes are called alleles.
- Genotype is the combination of alleles that an individual has for a certain gene, while phenotype is the appearance caused by the expression of the genotype.
- Incomplete dominance and codominance do not fit Mendel's rules because one allele does not entirely mask the other.
- In polygenic inheritance, many genes control a trait with each dominant allele having an additive effect.

Review Questions

1. What is a variant of a gene that occurs at the same place on homologous chromosomes?
2. What is the type of allele that only affects the phenotype in the homozygous condition?
3. What type of allele masks the expression of the recessive allele and is therefore expressed in the heterozygote?
4. What is the term for the specific alleles of an individual for a particular trait?
5. What is the term for the appearance of the organism, as determined by the genotype?
6. If a organism has a certain phenotype, such as a tall pea plant, does that mean it must have the same genotype?
7. What is the term for the pattern of inheritance where an individual has an intermediate phenotype between the two parents?
8. IQ in humans varies in humans with most people having an IQ of around 100, and with a few people at the extremes, such as 50 or 150. What type of inheritance do you think this might describe?
9. A dark purple flower is crossed with a white flower of the same species and the offspring

have light purple flowers. What type of inheritance does this describe?
10. What is the inheritance pattern where both alleles are expressed?

Further Reading / Supplemental Links

- http://en.wikipedia.org/wiki/Dominant_gene
- http://en.wikipedia.org/wiki/Polygenic_inheritance
- http://staff.jccc.net/pdecell/evolution/polygen.html
- http://www.curiosityrats.com/genetics.html
- http://www.estrellamountain.edu/faculty/farabee/BIOBK/BioBookgenintro.html

Vocabulary

allele An alternative form of a gene.

co-dominance A pattern of inheritance where both alleles are equally expressed.

genotype The genetic makeup of a cell or organism, defined by certain alleles for a particular trait.

heterozygous Having identical alleles for a particular trait.

homozygous Having two different alleles for a particular trait.

incomplete dominance A pattern of inheritance where the offspring has a phenotype that is halfway between the two parents' phenotypes.

phenotype The physical appearance that is a result of the genotype.

polygenic inheritance A pattern of inheritance where the trait is controlled by many genes and each dominant allele has an additive effect.

Points to Consider

- Hypothesize about the genetic differences between males and females.
- Can you name any human genetic disorders?
- If a baby inherits an extra chromosome, what might the result be?

6.3 Lesson 6.3: Human Genetics

Lesson Objectives

- List the two types of chromosomes in the human genome.
- Predict patterns of inheritance for traits located on the sex chromosomes.
- Describe how some common human genetic disorders are inherited.
- Explain how changes in chromosomes can cause disorders in humans.

Check Your Understanding

- How many alleles does an individual have for each gene/trait?
- How do we predict the probability of traits being passed on to the next generation?
- What do we call complexes of DNA wound around proteins that pass on genetic information to the next generation of cells?

Introduction

You might know someone who was born with a genetic disorder, such as cystic fibrosis or Down syndrome. And you might have wondered how someone inherits these types of disorders. It all goes back to Mendel! Mendel's rules laid the foundation for understanding the genetics of all organisms, including humans. We can apply Mendel's rules to describe how many human traits and genetic disorders are inherited. Some disorders are caused by a recessive allele, while other disorders are caused by a single dominant allele. Therefore, we can draw a Punnett square to predict the number of offspring that may be affected with these diseases, just like we predicted for other traits in the previous lessons. Since Mendel's time, we have also expanded our knowledge of inheritance and understand that genes are located on chromosomes. Now we can now explain special inheritance patterns that don't fit Mendel's rules.

Sex-linked Inheritance

What determines if a baby is a boy or a girl? Recall that you have 23 pairs of chromosomes, one pair of which are the sex chromosomes. Everyone has two sex chromosomes, X or Y, that determine our sex. Females have two X chromosomes, while males have one Y chromosome and one X chromosome. So if a baby inherits an X from the father and an X from the mother, it will be a girl. If the father's sperm carries the Y chromosome, it will be a boy. Notice that a mother can only pass on an X chromosome, so the sex of the baby is determined by the father. The father has a 50 percent chance of passing on the Y or X chromosome, hence it is a 50 percent chance whether a child will be a boy or a girl.

One special pattern of inheritance that doesn't fit Mendel's rules is **sex-linked inheritance,** referring to the inheritance of traits which are due to genes located on the sex chromosomes. The X chromosome and Y chromosome carry many genes and some of them code for traits that have nothing to do with determining sex. Since males and females do not have the same sex chromosomes, there will be differences between the sexes in how these sex-linked traits are expressed.

One example of a sex-linked trait is red-green colorblindness. People with this type of colorblindness cannot distinguish between red and green and often see these colors as shades of brown (**Figure** 6.9). Boys are much more likely to be colorblind than girls. That's because colorblindness is a sex-linked recessive trait. Boys only have one X chromosome, so if that chromosome carries the gene for colorblindness, they will be colorblind. As girls have two X chromosomes, a girl can have one X chromosome with the colorblind gene and one X chromosome with a normal gene for color vision. Since colorblindness is recessive, the dominant normal gene will mask the recessive colorblind gene. For a girl to be colorblind, she would have to inherit two genes for colorblindness, which is very unlikely. Many sex-linked traits are inherited in a recessive manner.

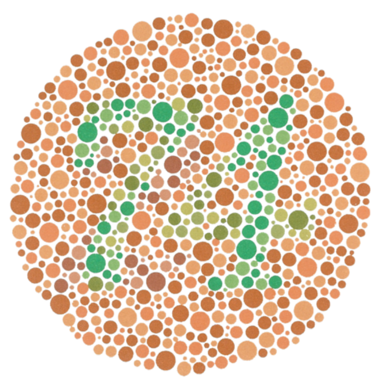

Figure 6.9: A person with red-green colorblindness would not be able to see the number. (2)

A woman can be a carrier of colorblindness, however. A **carrier** appears normal but is capable of passing on a genetic disorder to her child. Carriers for colorblindness have a heterozygous genotype of one colorblind allele and one normal allele. We can use a Punnett square to predict the probability of a carrier passing on the trait to her children. For example, if a woman who is a carrier for colorblindness has children, her boys would have a 50% chance of being colorblind and her girls have a 50% chance of being carriers.

Table 6.2:

	Xc	X
X	**XcX** (carrier female)	**XX** (normal female)
Y	**XcY** (colorblind male)	**XY** (normal male)

Human Genetic Disorders

Some human genetic disorders are also X-linked or Y-linked, which means the faulty gene is carried on these sex chromosomes. Other genetic disorders are carried on one of the other 22 pairs of chromosomes; these chromosomes are known as **autosomes** or autosomal chromosomes.

Some genetic disorders are caused by recessive or dominant alleles of a single gene on an autosome. These disorders would then have the same inheritance pattern as any other dominant or recessive trait. An example of an autosomal recessive genetic disorder is cystic fibrosis. Children with cystic fibrosis have excessively thick mucus in their lungs which makes it difficult for them to breathe. The inheritance of this recessive allele is the same as any other recessive allele, so a Punnett square can be used to predict the probability that two carriers of the disease will have a child with cystic fibrosis.

Table 6.3:

	F	f
F	**FF** (normal)	**Ff** (carrier)
f	**Ff** (carrier)	**ff** (affected)

Another recessive trait that we mentioned previously was sickle cell anemia. A person with two recessive alleles for the sickle cell trait (aa) will have sickle cell disease. In this disease the hemoglobin protein is formed incorrectly and the person's red blood cells are misshapen. A person who does not carry the sickle trait has a homozygous dominant genotype (AA). Remember the trait showed incomplete dominance, so a person who is heterozygous for the trait (Aa) would have some sickle-shaped cells and some normal red blood cells.

You can also use a simple Punnett square to predict the inheritance of a dominant autosomal disorder, like Huntington's disease. If one parent has Huntington's disease, what is the chance of passing it on to their children? If you draw the Punnett square, you will see that there is a 50 percent chance of the disorder being passed on to the children. Huntington's disease causes the brain's cells to break down, leading to muscle spasms and personality changes. Unlike most other genetic disorders, the symptoms usually do not become apparent until middle age.

Genetic diseases can also be carried on the sex-chromosomes. An example of a recessive sex-linked genetic disorder is hemophilia. A hemophiliac's blood does not clot, or clots very slowly, so he or she can easily bleed to death. As with colorblindness, males are much more likely to be hemophiliacs since the gene is on the X chromosome. Because Queen Victoria of England was a carrier of hemophilia, this disorder was once common in European royal families. Several of her grandsons were afflicted with hemophilia, but none of her granddaughters were affected by the disease, although they were often carriers. Because at the time medical care was very primitive, often hemophiliacs bled to death, and usually at a young age. Queen Victoria's grandson Frederick died at age 3, and her grandson Waldemar died at age 11 (**Figure** 6.10).

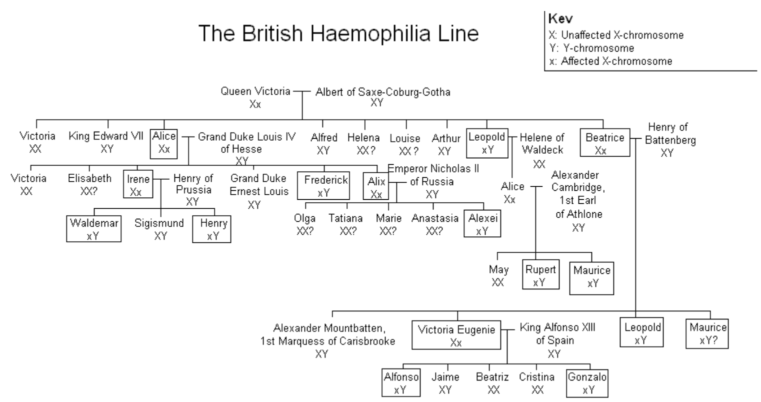

Figure 6.10: A pedigree chart shows all the phenotypes for a particular trait in the family. This pedigree chart traces back the occurrence of hemophilia in the British royal family. Those individuals with boxes around them are either female carriers of the trait or males inflicted with the trait. (13)

Many genetic disorders are recessive, meaning that an individual must be homozygous for the recessive allele to be affected. Sometimes these disorders are lethal (deadly), however, heterozygous individuals (unaffected individuals with one dominant allele and one recessive allele) survive. This allows the allele that causes the genetic disorder to be maintained in a population's **gene pool.** A gene pool is the complete set of unique alleles in a species or population. A mutation is a change in the DNA sequence. New mutations are constantly being generated in a gene pool.

Pedigree Analysis

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** 6.11 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.

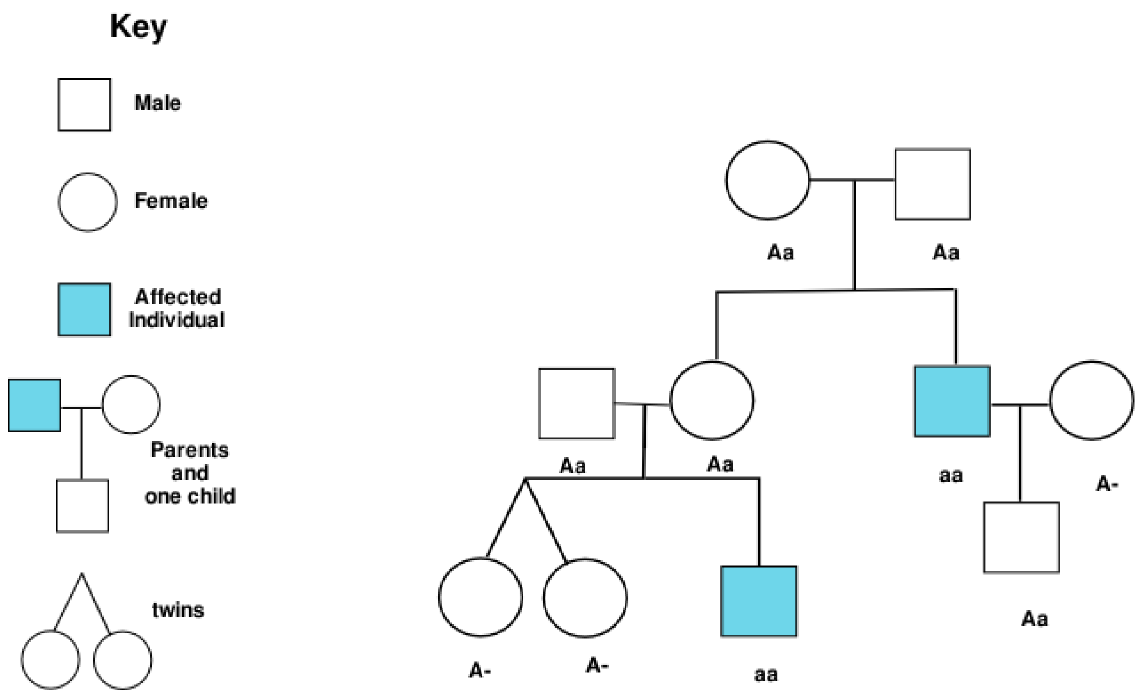

Figure 6.11: In a pedigree, squares symbolize males, and circles represent females. A horizontal line joining a male and female indicates that the couple had offspring. Vertical lines indicate offspring which are listed left to right, in order of birth. Shading of the circle or square indicates an individual who has the trait being traced. The inheritance of the recessive trait is being traced. A is the dominant allele and a is recessive. (1)

Chromosomal Disorders

Some children are born with genetic defects that are not carried by a single gene. Instead, an error in a larger part of the chromosome or even in an entire chromosome causes the disorder. Usually the error happens when the egg or sperm is forming. One common example is Down syndrome (**Figure** 6.12). Children with Down syndrome are mentally disabled and have collection of recognizable physical deformities. Down syndrome occurs when a baby receives an extra chromosome from one of his or her parents. Usually a child would have one chromosome 21 from your mother and one chromosome 21 from your father. But in an individual with Down syndrome, there are three copies of chromosome 21. Down syndrome is also known as trisomy 21.

Figure 6.12: A child with Down syndrome. (16)

Another example of a chromosomal disorder is Klinefelter syndrome, in which a male inherits an extra "X" chromosome. These individuals have underdeveloped sex organs and elongated limbs, and have difficulty learning new things. Outside of chromosome 21 and the sex chromosomes, most embryos with extra chromosomes do not even make it to the fetal stage. Because chromosomes carry many, many genes, a disruption of a chromosome potentially causes severe problems with development of the fetus.

Besides diseases caused by duplicated chromosomes, other chromosomal disorders occur when the structure of a chromosome is disrupted. For example, if a tiny portion of chromosome 5 is missing, the individual will have cri du chat (cat's cry) syndrome. These individuals have misshapen facial features and the infant's cry resembles a cat's cry.

Lesson Summary

- Some human traits are controlled by genes on the sex chromosomes.
- Human genetic disorders can be inherited through recessive or dominant alleles, and they can be located on the sex chromosomes or autosomes.
- Changes in chromosome number can lead to disorders like Down syndrome.

Review Questions

1. How many chromosomes do you have in each cell of your body?
2. How is Down syndrome inherited?
3. A son cannot inherit colorblindness from his father. Why not?
4. One parent is a carrier of the cystic fibrosis gene, while the other parent does not carry the allele. Can their child have cystic fibrosis?

Further Reading / Supplemental Links

- http://www.articlesbase.com/health-articles/what-is-haemophilia-412305.html
- http://www.scribd.com/doc/1018249/lectureChromsomes-and-Human-Genetics-Guevedoces
- http://geneticdisorderinfo.wikispaces.com/
- http://learn.genetics.utah.edu/units/disorders/karyotype/karyotype.cfm
- http://www.hhmi.org/biointeractive/vlabs/cardiology/index.html
- http://en.wikipedia.org/

Vocabulary

autosomes The chromosome other than the sex chromosomes.

carrier A person who is heterozygous for a recessive genetic disorder; the person does not have the disease but can pass the disease allele to the next generation.

sex-linked trait A trait that is due to a gene located on a sex chromosome, usually the X-chromosome.

Points to Consider

- Human cloning is illegal in many countries. Do you agree with these restrictions?

- Why would it be helpful to know all the genes that make up human DNA?
- It may be possible in the future to obtain the sequence of all your genes. Would you want to take advantage of this opportunity? Why or why not?

6.4 Lesson 6.4: Genetic Advances

Lesson Objectives

- Explain how clones are made.
- Explain how vectors are made.
- Explain what sequencing a genome tells us.
- Describe how gene therapy works.

Check Your Understanding

- What part of the cell contains the genetic material?
- What are the base pairing rules for DNA?

Introduction

Since Mendel's time, there have been rapid advances in the understanding of genetics. As scientists understand better how DNA works, they can develop technologies that allow us to reveal the genetic secrets encoded in our DNA and even alter an organism's DNA. Genetic engineering (or *biotechnology* or *DNA technology*) has helped us better understand and predict the inheritance of genetic diseases, produce new medicines, and even produce new food products. DNA technology has also made an impact on fighting crime. Because DNA is unique to an individual, the DNA in just a few hairs at a crime scene can help identify a criminal. This technology, known as DNA fingerprinting, has also helped innocent imprisoned people to appeal their case and clear their names. DNA technology has revolutionized not only criminal justice, but also many other aspects of our lives.

Recombinant DNA

Recombinant DNA is the combination of DNA from two different sources. It is useful in gene cloning and in identifying the function of a gene, as well as producing useful proteins. Human insulin for treating diabetes has been produced through recombinant DNA methods. In this process, a gene of interest (or piece of DNA of interest) is placed into a host cell, such as a bacterium, so the gene can be copied (and cloned) and the protein that results from that gene can be produced.

To place the gene of interest into a host cell, a **vector,** or carrier molecule, is needed to the carry foreign DNA into the host cell. Bacteria have small accessory rings of DNA in the cytoplasm, called **plasmids**. When putting foreign DNA into a bacterium (a host cell), the plasmids are often used as a vector. Viruses can also be used as vectors.

The first step of making recombinant DNA involves a **restriction enzyme** that cuts the vector and the foreign (exogenous) DNA. Restriction enzymes cut DNA at specific sequences, such as GAATTC as shown in **Figure** 6.13 . There are more than 3,000 known restriction enzymes, most cutting the DNA at a unique sequence. This reaction results in the plasmid opening up a gap with "sticky ends," which can attach with the complimentary base pairs on the sticky ends of the foreign DNA. Then the enzyme **DNA ligase** seals the foreign DNA in its new place inside the plasmid. These altered plasmids are introduced back into the bacteria, a process called **transformation** (**Figure** 6.14). The bacteria will express the foreign gene.

Figure 6.13: Restriction enzymes cut DNA at specific sequences, in this example the sequence "GAATTC." The enzyme cuts between the G and A on each strand, producing overhanging "sticky ends." (5)

One application of recombinant DNA technology is producing the protein insulin, which is needed to treat diabetes. Previously, insulin had been extracted from the pancreases of animals. Through recombinant DNA technology, bacteria were created that carry the human gene which codes for the production of insulin. These bacteria become tiny factories that produce this protein. A step-by-step depiction of the cloning of the insulin gene is shown below in (**Figure** 6.15).

Cloning

Cloning is the process of creating an exact replica of an organism. The clone's DNA is exactly the same as the parent's DNA. Bacteria and plants have long been able to clone themselves through processes of asexual reproduction. In animals, however, cloning does not happen naturally.

Animals can now be cloned in a laboratory, however. In 1997, a sheep named Dolly was the first mammal ever to be successfully cloned. The process of producing an animal like Dolly

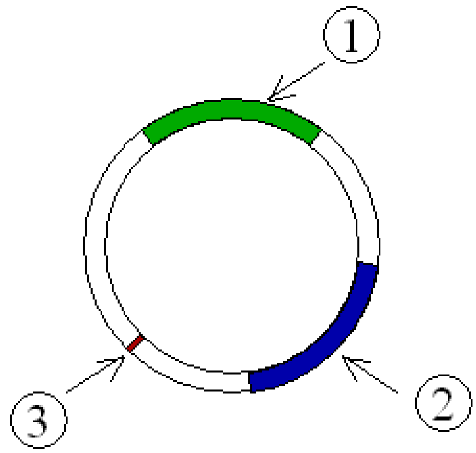

Figure 6.14: This image shows a line drawing of a plasmid. The plasmid is drawn as two concentric circles that are very close together, with two large segments and one small segment depicted. The two large segments (1 and 2) indicate antibiotic resistances usually used in a screening procedure, and the small segment (3) indicates an origin of replication. The resulting DNA is a recombinant DNA molecule. (3)

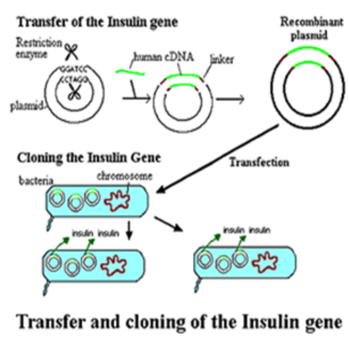

Figure 6.15: A step-by-step depiction of the cloning of the insulin gene. The plasmid is opened up with restriction enzymes and the gene of interest (human cDNA) is inserted into the plasmid with complementary linkers, producing the recombinant plasmid. The plasmid is transfected into bacterial cells, where the human protein is produced. (17)

starts with a single cell from the animal that is going to be cloned. In the case of Dolly, cells from the mammary glands were taken from the adult that was to be cloned. These cells are called **somatic,** meaning they come from the body and are not gametes like sperm or egg. Remember that somatic cells have a diploid number of chromosomes. Next, the nucleus was removed from this cell. The nucleus was placed in a donor egg that had already had the nucleus removed. The new cell then divided after the stimulation of an electric shock, and development proceeded normally just as if the embryo had formed naturally. The resulting embryo was implanted in a surrogate mother sheep, where it continued its development. This process is shown in **Figure** 6.16.

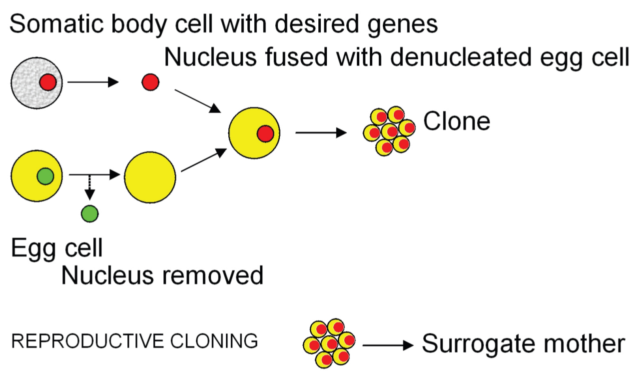

Figure 6.16: To clone an animal, a nucleus from the animal's cells are fused with an egg cell (in which the nucleus has been removed) from a donor. (14)

Cloning is not always successful, though. Most of the time, this cloning process does not result in a healthy adult animal. The process has to be repeated many times until it works. In fact, 277 tries were needed to produce Dolly. This high failure rate is one reason that human cloning is banned in the United States. In order to produce a cloned human, many attempts would result in the surrogate mothers experiencing miscarriages, stillbirths, or deformities in the infant. There are also many additional ethical considerations related to human cloning.

Human Genome Project

A person's genome is all of his or her genetic information; in other words, the human genome is all the information that makes us human. The **Human Genome Project** (**Figure** 6.17) was an international effort to sequence all 3 billion bases that make up our DNA and to identify within this code the over 20,000 human genes. Scientists also completed a chromosome map, identifying where the genes are located on each of the chromosomes. The Human Genome Project was completed in 2003. Though the Human Genome Project is finished, analysis of the data will continue for many years.

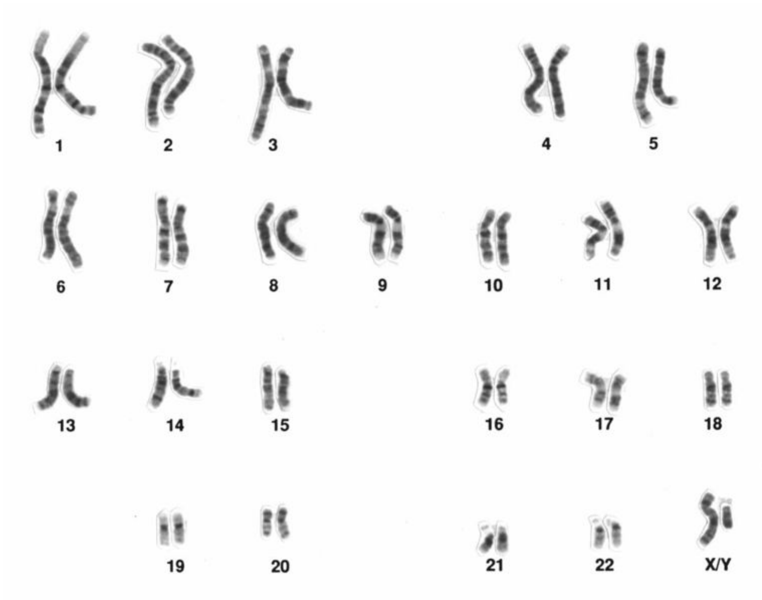

Figure 6.17: To complete the Human Genome Project, all 23 pairs of chromosomes in the human body were sequenced. Each chromosomes contains thousands of genes. This is a karyotype, a visual representation of an individual's chromosomes lined up by size. (8)

There are many exciting applications of the Human Genome Project. The genetic basis for many diseases can be more easily determined, and now there are tests for over 1,000 genetic disorders. The National Institutes of Health, the United States government's premiere biomedical research community, is also looking for ways to reduce the costs of sequencing so that people can have a map of their individual genome. Although some disorders are caused by a single gene, many other illnesses are caused by a combination of several genes and a person's lifestyle. Analysis of your own genome could determine if you are at risk for specific diseases. Knowing you might be genetically prone to a certain disease would allow you to better seek preventive lifestyle changes and medical screenings.

A **genetic map** shows the location (or **loci**) of a gene on a chromosome. Genetic maps are important tools to help researchers understand genes and genetic diseases. Knowing where genes are in relation to other genes and knowing the order of genes on a chromosome is an important aspect of human genetics. The frequency of recombination (crossing-over during prophase I of meiosis) allows geneticists to estimate the distance between loci. Because crossing-over occurs relatively rarely at any location along the chromosome, the frequency of recombination between two locations depends on their distance. The farther apart genes are on the same chromosome, the more likely there is to be a cross-over event between them. The likelihood of a cross-over event between two closely located genes (said to be **linked**) is small.

Gene Therapy

Gene therapy is the insertion of genes into a person's cells to cure a genetic disorder. There are two main types of gene therapy; one done inside the body and one done outside the body. In *ex vivo* gene therapy, done outside the body, cells are removed from the patient and the proper gene is inserted using a virus as a vector. Then the modified cells are placed back into the patient. One of the first uses of this type of gene therapy was in the treatment of a young girl with a rare genetic disease, Adenosine deaminase deficiency, or ADA deficiency. People with this disorder are missing the ADA enzyme, which breaks down a toxin called deoxyadenosine. If the toxin is not broken down, it accumulates and destroys immune cells. As a result, individuals with ADA deficiency do not have a healthy immune system to fight off infections. In the gene therapy treatment for this disorder, bone marrow stem cells were taken from the girl's body and the missing gene was inserted in these cells outside the body. Then the modified cells were put back into her bloodstream. This treatment proved sufficient to restore the function of her immune system, but only with continual repeated treatments.

During *in vivo* gene therapy, done inside the body, the vector with the gene of interest is introduced directly into the patient and taken up by the patient's cells. The vector is inserted where the gene product is needed. For example, cystic fibrosis gene therapy is targeted at the respiratory system, so a solution with the vector can be sprayed into the patient's nose. Recently *in vivo* gene therapy was also used to partially restore the vision of three young adults with a rare type of retinal disease that is congenital, meaning present at birth.

Biotechnology in Medicine and Agriculture

There are many applications of genetic information, including applications in medicine and agriculture. These applications show daily the significance of biotechnology, and the impact biotechnology has on our society.

Medicine

As mentioned above, one application of recombinant DNA technology is producing the protein insulin. Using biotechnological techniques, 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. Recombinant DNA technology has allowed mass quantities of insulin to be produced, treating the growing population that relies on this protein.

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.

Agriculture

Biotechnology has also led scientists to develop useful applications 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.

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 harsh conditions. 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 scientists 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** 6.18), 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 DNA has been extensively characterized. Scientists have identified a gene from this plant, At-DBF2, that gives the plant 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 a rice virus. In Africa, this virus destroys much of the rice crops and makes the surviving plants more susceptible to fungal infections.

Lesson Summary

- Using recombinant DNA technology, a foreign gene can be inserted into an organism's DNA.

Figure 6.18: Thale cress. (10)

- Cloning of mammals is still being perfected, but several cloned animals have been created by implanting the nucleus of a somatic cell into a cell in which the nucleus has been removed.
- The Human Genome Project produced a genetic map of all the human chromosomes and determined the sequence of every base pair in our DNA.
- Gene therapy involves treating an illness caused by a defective gene through the use of a vector to integrate a normal copy of the gene into the patient.

Review Questions

1. What is the enzyme used to cut DNA at specific points?
2. What is the term for all the genetic information of the human species?
3. What are the rings of accessory DNA in bacteria that are often used as a vector in genetic engineering?
4. What is the term for producing identical copies of an organism?
5. Can gene therapy cure a disease caused by a virus?
6. What is the vehicle used to introduce foreign DNA into an organism?
7. What is one disease that genetic therapy can help treat?
8. What supplies the cytoplasm of the clone's cells during the cloning of an organism?
9. What is one application of recombinant DNA technology?
10. Is gene therapy for ADA deficiency a permanent fix?

Further Reading / Supplemental Links

- http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml
- http://history.nih.gov/exhibits/genetics/sect4.htm
- http://learn.genetics.utah.edu/units/disorders/whataregd/ada/
- http://www.lifesitenews.com/ldn/2007/nov/07112003.html
- http://www.le.ac.uk/ge/genie/vgec/sc/genomics.html
- http://en.wikipedia.org/wiki/Recombinant_DNA
- http://www.hhmi.org/biointeractive/vlabs/transgenic_fly/index.html
- http://www.groundreport.com/World/Scientists-to-clone-rhino

Vocabulary

cloning Creating an identical copy of an individual with the same genes.

DNA ligase Enzyme that joins DNA fragments together.

gene therapy Treatment that provides a new gene to replace a defective gene; potentially "cures" a genetic disease.

human genome project International effort to sequence all the base pairs in human DNA.

plasmid An accessory circle of DNA in bacteria.

recombinant DNA DNA formed bu the combination of DNA from two different sources, such as placing a human gene into a bacterial plasmid.

somatic cell A body cell; not a gamete.

transformation The process by which bacteria pick up foreign DNA and incorporate it in their genome.

vector A vehicle, such as a plasmid, used to transfer foreign DNA into an organism.

Points to Consider

Next we begin to discuss evolution, the change in species over time.

- Fossils provide evidence of evolution, but what is a fossil?
- If two animals are similar in structure, would you guess they are closely related? Why or why not?

Image Sources

(1) Rozzychan. http://en.wikipedia.org/wiki/Image:PedigreechartB.png. CC-BY-SA 2.5.

(2) http://en.wikipedia.org/wiki/Image:Ishihara_9.png. Public Domain.

(3) http://commons.wikimedia.org/wiki/Image:Example_plasmid.png. GNU-FDL.

(4) NIH. http://commons.wikimedia.org/wiki/Image:Codominant.jpg. Public Domain.

(5) http://commons.wikimedia.org/wiki/Image:Restriction_enzyme.jpg. Public Domain.

(6) NIH. http://commons.wikimedia.org/wiki/Image:Redbloodcells.jpg. Public Domain.

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(8) http://commons.wikimedia.org/wiki/Image:Human_male_karyotpe_high_resolution.jpg. Public Domain.

(9) *Gregor Mendel*. Public Domain.

(10) *Thale cress.*. GNU-FDL.

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(16) *A child with Down syndrome.*. CC-BY 2.0.

(17) Dr. Kathleen A. Marrs. http://images.google.com/imgres?imgurl=http://www.madison.k12.ky.us/ms/departments/science/whatisbiology/assests/pic17b.gif.

(18) *The Punnett Square of a cross between two purple flowers (Bb)*. GNU-FDL.

Chapter 7

Evolution

7.1 Lesson 7.1: Evolution by Natural Selection

Lesson Objectives

- Understand that inherited traits, such as the basic color of skin or a person's bone structure, are passed on to future generations.
- Understand that acquired traits, such as a tan or being good at soccer, are not passed on to future generations (they are not inherited).
- Understand that evolution is change of an inherited trait in a population over many generations, such as the change of the color of moths living on an island over many generations.
- Understand that natural selection means that organisms with traits that help them survive in their environment are more likely to survive than organisms without that beneficial trait.
- Understand how evolution explains:
  - Why populations change.
  - Why there are so many different kinds of organisms on Earth.
  - Why some organisms that look alike only distantly related.
  - Why some organisms that look very different actually closely related?
- Know that both Darwin and Wallace developed the theory of evolution by natural selection at the same time.

Check Your Understanding

- What does the word evolution refer to when used in day to day conversations?
- What does biological evolution mean?

- Who primarily proposed the theory of evolution by natural selection?

Introduction

Biological evolution is change in species over time. The idea of evolution was proposed by many people before Charles Darwin (**Figure** 7.1) began collecting evidence for the idea. Scientists for hundreds of years had hypothesized that species change over time. But it was not until Darwin published his research and detailed analysis that the idea of evolution started to gain widespread acceptance. Darwin's theory of evolution by natural selection brings all fields of biology together and illuminates nearly every aspect of biology. As one famous biologist said, "Nothing in biology makes sense except in the light of evolution."

Figure 7.1: Charles Darwin was one of the most influential scientists who has ever lived. Darwin introduced the world to the theory of evolution by natural selection, which laid the foundation for how we understand the living world today. (18)

Evolution by natural selection explains:

- The tremendous variety of organisms on Earth.
- Why some organisms that resemble each other are distantly related.
- Why some organisms that do not resemble each other are closely related.

There are three parts to Darwin's Theory of Evolution by Natural Selection.

1. Evolution, which is change in species over multiple generations (**Figure** 7.2).
2. Natural selection, in which individuals of a population that are most likely to survive and reproduce are also most likely to pass on traits that have a genetic basis to any offspring.
3. Adaptation, which are traits that help a plant or animal survive and reproduce in a particular environment. Adaptations are the result of natural selection. For example, light-colored moths on dark trees might be easier for birds to see and catch than dark moths on dark-colored trees. If the moths' color has a genetic basis, then after many generations of birds catching more light moths than dark moths, the population of moths will consist mostly of dark moths.

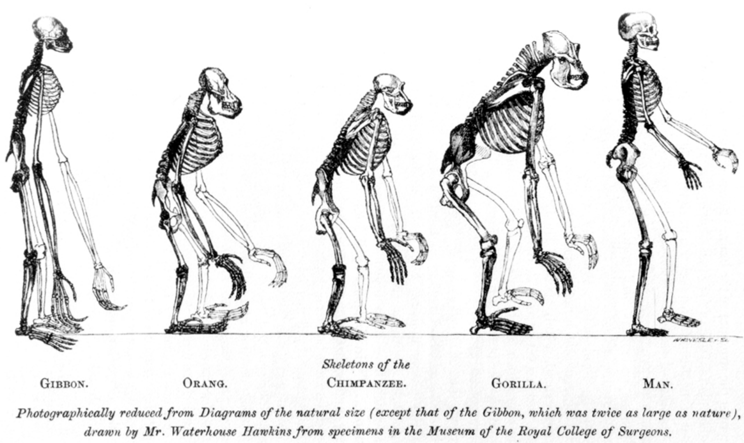


Figure 7.2: Humans and the other apes in this drawing all evolved from a common apelike ancestor. (2)

In everyday English, "evolution" simply means to "change" or a "stepwise change from simple to complex." In biology, evolution means change in the inherited traits of a group of organisms over multiple generations (**Figure** 7.3). Biological evolution has changed biologists' understanding of all life on Earth.

Darwin's Observations

Most people in the world did not become aware of the theory of evolution until 1859, when Charles Darwin published his book *On the Origin of Species by Means of Natural Selection*. This book described the observations and evidence that he collected over 20 years of intensive research, beginning with a five-year voyage around the world on a British research ship, the *HMS Beagle*. During this five-year voyage (**Figure** 7.4), Darwin was able to make observations about plants and animals spread around the world, and to collect specimens to study when he returned to England. Each time the Beagle stopped at a port to do some

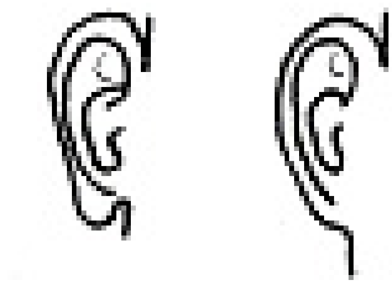


Figure 7.3: Human earlobes may be free or attached. You inherited the particular shape of your earlobes from your parents. Inherited traits are influenced by genes, which are passed on to offspring and future generations. Your summer tan is not passed on to your offspring. Natural selection only operates on traits like earlobe shape that have a genetic basis, not on traits like a summer tan that are "acquired." (4)

trading, Darwin went on land to explore and look for the local plants, animals, and fossils. One of the most important things Darwin did was to keep a diary. He took extremely detailed notes and drawings about everything he saw as well as his thoughts.

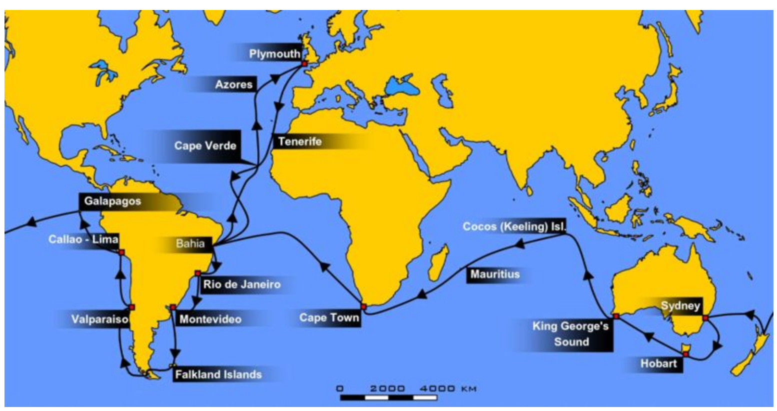


Figure 7.4: Charles Darwin's famous five year voyage was aboard the *HMS Beagle* from 1831-1836. (7)

The Galápagos Islands

The around the world voyage of the *HMS Beagle* was mostly to map the coastline of South America. Darwin's best known discoveries were made on the Galápagos Islands (**Figure** 7.5), 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's Theory of Evolution by Natural Selection was a result of his observations and over 20 years of examining the specimens he had collected and sent back to England, many of which came from these islands.

Figure 7.5: The Galápagos Islands are a group of 16 volcanic islands 972 km off the west coast of South America. The islands are famous for their many species found nowhere else. (35)

Darwin was amazed by the array of life he saw on the Galápagos Islands. He saw animals unlike anything he had ever seen before. Darwin was struck by how the same kind of animal differed from one island to another. For example, the iguanas (large lizards) differed between islands (**Figure** 7.6). The members of one iguana species spent much of their time swimming and diving underwater for seaweed, while those of another iguana species lived on land and ate cactus. In England, he was accustomed to watching cormorants fly, so he was surprised to find flightless cormorants on the islands alongside flying cormorants.

Giant Tortoises

Giant tortoises (**Figure** 7.7), large enough for two men to ride on, plodded across the islands and foraged on super tough leaves. Some of the tortoise species were found on only one island. Darwin was fascinated by the number of ways that organisms were well-suited to their environments. Even the tortoise shells were specially adapted to the conditions. Tortoises that ate plants near the ground had rounded shells, while the tortoises that stretched their necks to reach plants higher in shrubs had shells that bent upwards, allowing them to stretch their necks upward (**Figure** 7.8).

Figure 7.6: The Galápagos land iguanas are among the signature animals of the Galápagos Islands. (32)

Figure 7.7: The name “Galápagos” means “giant tortoise.” When Darwin arrived on the Galápagos Islands, he was amazed by the size and variety of shapes of these animals. The giant tortoise is a unique animal found only in the Galápagos Islands. There only about 200 tortoises remaining on these islands. (30)

Figure 7.8: This tortoise is able to reach leaves high in shrubs with its long neck and curved shell. (12)

Darwin's Finches

The most extensively studied animals on the Galápagos are the finch species (birds) (**Figure 7.9**). When Darwin first observed the finches on the islands, he did not even realize they were all finches. But when he studied them further, he realized they were all the same type of bird, and that each island had its own distinct species of finch. The birds on different islands had many similarities, but their beaks differed in size and shape.

In his diary, Darwin pointed out how each animal is well-suited for its particular environment. The shape of the finch's beaks on each island were well-matched with the seeds available on their particular island, but not the seeds on other islands. A larger and stronger beak was needed to break open large seeds and a small beak was needed to feed on some of the smallest seeds.

Darwin also noticed how different species were distributed around the world. The finch, tortoise and other species found on the Galápagos Islands were similar to species on South America, the nearest continent. Yet they also differed. Likewise, species he saw on islands *near* Africa were similar to, but different from species *on* Africa.

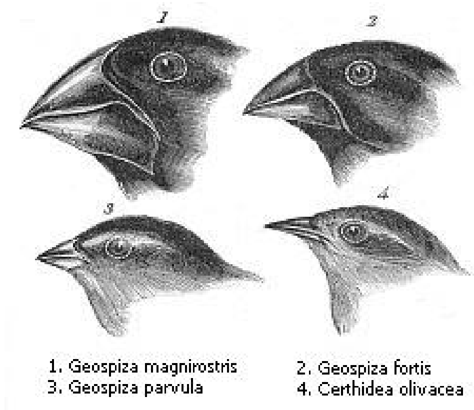


Figure 7.9: Four of Darwin's finch species from the Galápagos Islands. The birds came from the same finch ancestor. They evolved as they adapted to different food resources on different islands. The first bird uses its large beak to crack open and eat large seeds. Bird #3 is able to pull small seeds out of small spaces. (31)

Return to England

When Darwin returned to England five years later, he did not rush to announce his discoveries. Unlike other naturalists before him, Darwin did not want to present any ideas unless he had strong evidence supporting them. Instead, once Darwin returned to England, he spent over twenty years examining specimens, talking with other scientists and collecting more information before he presented his theories. Darwin's observations eventually resulted in the Theory of Evolution by Natural Selection. His now famous book, *The Origin of Species* is a diary of his explorations and discussion on how he interpreted his observations (**Figure** 7.10).

Other Influences on Darwin

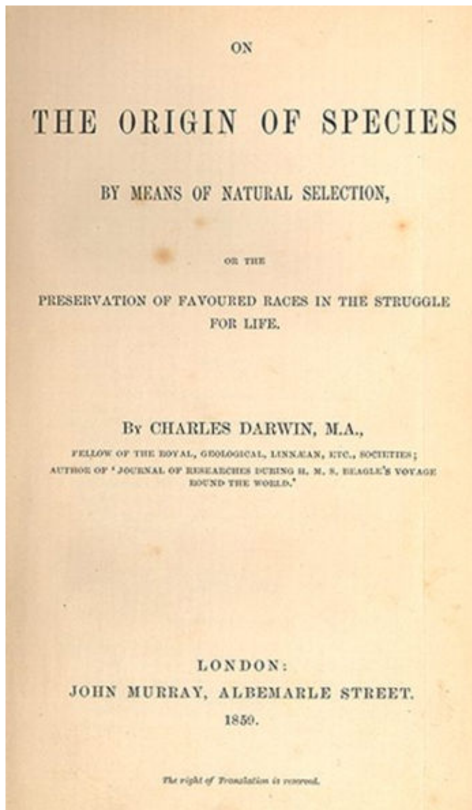
How did Darwin come up with his theories? Some of Darwin's idea conflicted with widely held beliefs, included those from religious leaders, such as:

- All organisms never change and never go extinct, they are fixed.
- The world is only about 6,000 years old.

It was because of these widely held beliefs that delayed Darwin from presenting his findings.

Charles Darwin was influenced by the ideas from several people.

Before his voyage on the Beagle:



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

Figure 7.10: Charles Darwin presented the Theory of Evolution by Natural Selection in this book. The theories were based on evidence he collected and tested. (29)

1. Jean-Baptiste Lamarck proposed the idea that evolution occurs. However, Darwin differed with Lamarck on several other points. Lamarck proposed that traits acquired during one's lifetime could be passed to the next generation.
2. Darwin's grandfather, Erasmus Darwin, wrote a book called *Zoonomia*. Charles Darwin was influenced by many of his grandfather's ideas including his descriptions of how species change (evolve) through artificial selection. During artificial selection, people choose specific traits to pass to the next generation, such as with horse or dog breeding (See below).
3. Charles Lyell, a well-known geologist and one of Darwin's instructors. Darwin learned about geology, paleontology and the changing Earth from Lyell. These findings suggested the Earth must be much older than 6,000 years.
4. Thomas Malthus: Darwin's ideas of natural selection were inspired by reading an essay by Thomas Malthus, an economist who suggested that humans could overpopulate and potentially exhaust food supplies. Darwin thought this must be especially true for animals, as they have a tendency to have more offspring than people have. There would therefore be a competition for survival.
5. Charles Darwin came upon some of his ideas about natural selection and adaptations from reading about artificial selection and breeding dogs. All dogs, from Chihuahuas to St. Bernards are part of the same species as wolves (*Canis lupus*). Humans created the different breeds of dogs by selecting dogs with specific traits to breed together. For example, greyhounds were created by selecting the fastest runners and breeding them together (**Figure** 7.11).
6. After the Voyage of the Beagle: Alfred Russel Wallace, another naturalist, also developed a theory of evolution by natural selection. Alfred Wallace toured South American and came up with a very similar theory of evolution by natural selection at the same time that Darwin did. Darwin and Wallace presented their theories and evidence in public together. Because of the vastness of Darwin's data, and his book, he is mostly credited and associated with this theory.

Natural Selection and Adaptation

The Theory of Evolution by Natural Selection means that the inherited traits of a population change over time through natural selection. Inherited traits are features that are passed from one generation to the next. For example, your eye color is an inherited trait (you inherited from your parents). Acquired traits are features such strong muscles from working out.

Natural selection happens when some organisms have traits that make them better suited (they have better accommodation) to live in a certain environment than others. They are more likely to survive, reproduce and pass their traits on to future generations than those without the special traits. The process of natural selection helps us understand how organisms appear to be so well suited or adapted to their environments. Every plant and animal depends on its traits to survive. Survival may include getting food, building homes, and

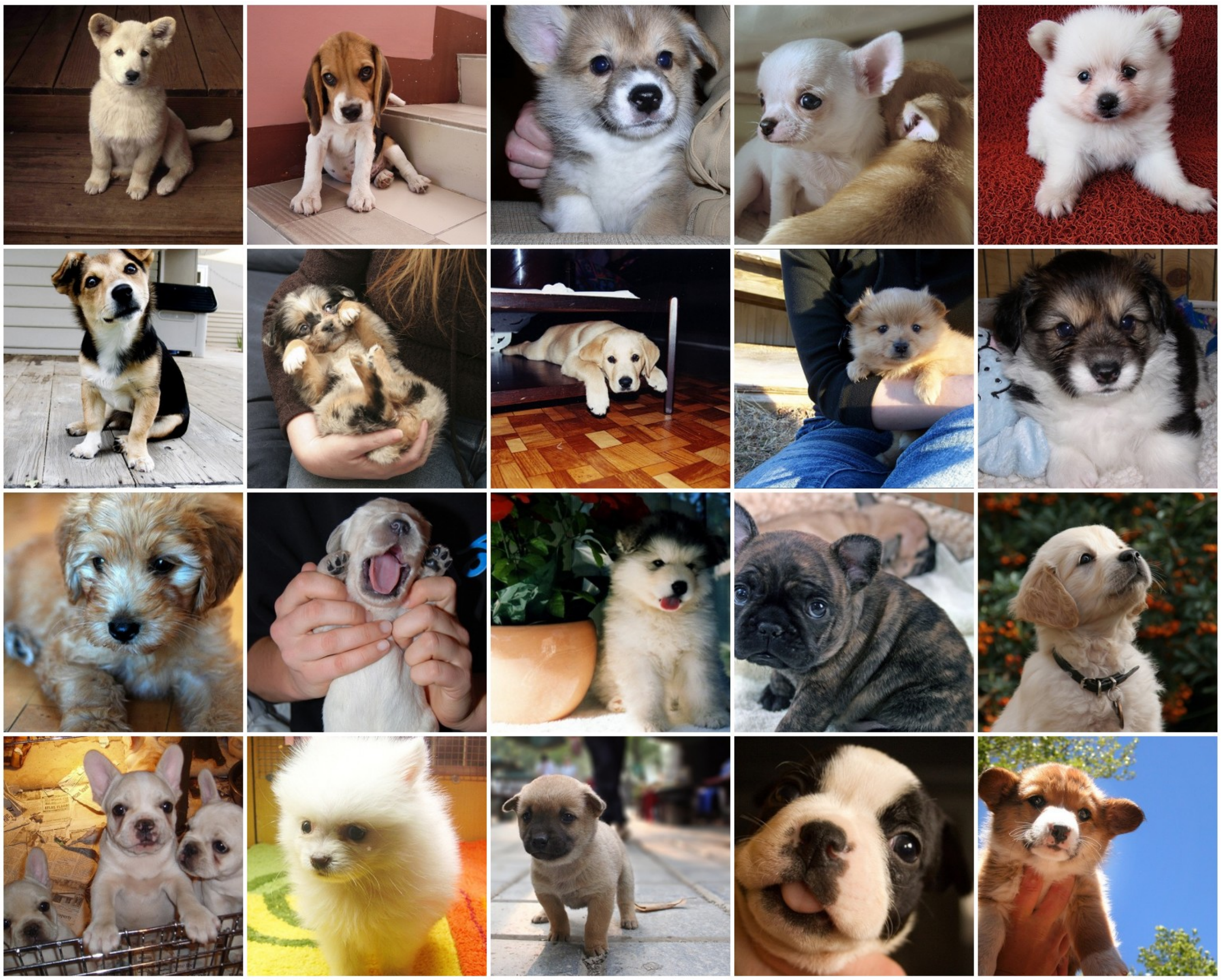


Figure 7.11: Darwin's grandfather had a big influence on Darwin's ideas by introducing him to artificial selection of dogs and horses. Humans have created hundreds of dog breeds by selecting which dogs to breed based on certain features, such as size, coloration, speed, or facial features. (23)

attracting mates. Most of these traits have been changed through natural selection so they allow a plant, animal, or bacteria to survive and reproduce relatively well in their environments. These traits are called adaptations. As environments have changed considerably over time, organisms must constantly adapt to those environments. It is the great diversity of species that increases the chance that at least some organisms adapt and survive any major changes in the environment.

Imagine how in winter dark fur makes a rabbit easy for fox to spot and catch in the snow. Natural selection suggests that white-fur is an advantageous trait that improves the chance that a rabbit will survive, reproduce and pass the trait of white fur on to future generations (**Figure** 7.12). Dark fur rabbits will become uncommon.

Figure 7.12: In winter, the fur of arctic hares turns white. The camouflage may make it more difficult for fox and other predators to locate hares against the white snow. (27)

Polygenic Inheritance and Natural Selection

But natural selection leading to evolution does not just select for certain individuals, it selects for groups. More than one individual must adapt to the environment to maintain a population. Natural selection determines which groups of organisms survive, based on their traits, and which do not, that is, natural selection determines the differential survival of groups of organisms.

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 continuous spectrum of phenotypic values which often show a bell curve pattern of variation.

Given this pattern of phenotypic variability, natural selection can take three forms (**Figure** 7.14). We will use the hypothetical color distribution in this figure to illustrate the three

Figure 7.13: Natural selection determines the survival of groups of organisms. Flight as shown in these geese is an evolutionary step that probably aided in the survival of many birds. (15)

types of selection. **Directional selection** shifts the frequency curve away from the average by favoring individuals with an extreme form of the variation. The curve would still be bell-shaped, but it would have shifted to the left or right, in the direction of the lighter or darker alleles. **Stabilizing selection** selects for a group of phenotypically average individuals, with individuals with either extreme phenotype selected against. **Disruptive selection** selects for groups of individuals with extreme phenotypes, selecting against individuals with the average phenotype.

Lesson Summary

- Evolution is change in species over multiple generations.
- Natural selection is how evolution occurs.
- Adaptations are the result of natural selection.
- Charles Darwin is credited with developing the Theory of Evolution by Natural Selection
- Darwin collected much of his evidence on a five year voyage around the world, with much of his data collected on the Galápagos Islands.
- The work of many others contributed to Darwin's theory.

Review Questions

1. What is biological evolution?

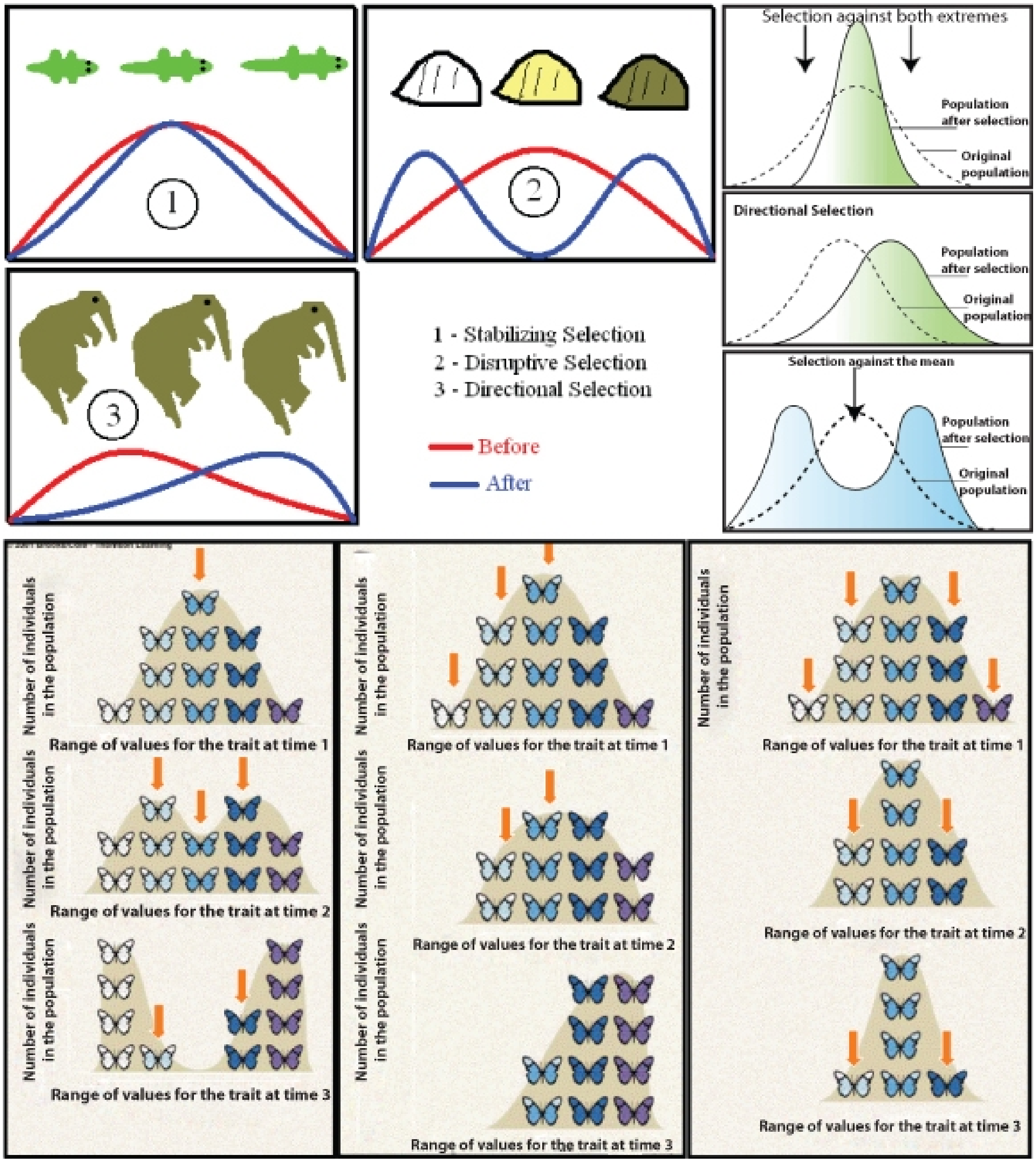


Figure 7.14: Three types of selection can alter allele frequencies, causing microevolution. The effect of stabilizing selection (1) is to select for the average phenotype, reducing variation. Disruptive selection (2) results in two different populations, which may eventually be isolated from one another. Directional selection (3) selects for a group of individuals with a single characteristic. (20)

2. What is natural selection?
3. What is adaptation?
4. What is the difference between an inherited trait and an acquired trait?
5. What was the name of the ship that Darwin traveled on?
6. What is the name of the islands where Darwin studied evolution?
7. A giraffe's long neck allows the giraffe to eat leaves from high in the tree. This is an example of an ___________________.
8. Who proposed a theory of evolution by natural selection that was similar to Darwin's theory?

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Vocabulary

acquired trait A feature that an organism gets during its lifetime in response to the environment (not from genes); not passed on to future generations through genes.

adaptation Beneficial traits that help an organism survive in its environment. Organisms with beneficial traits are more likely to survive, reproduce and pass their traits on to future generations than those without the special traits. These traits are called adaptations.

artificial selection Selection in which people choose specific traits to pass to the next generation, such as with horse or dog breeding.

evolution A process in which something passes by degrees to a different stage, such as a living organism turning into a more advanced or mature organism; the change of the inherited traits of a group of organisms over many generations.

evolution by natural selection The changes in the inherited traits of a population from one generation to the next; due to a process where organisms that are best suited to their environments have greater survival and reproductive success.

Galápagos Islands A group of islands in the Pacific off South America; owned by Ecuador; known for unusual animal life. Many scientists, including Charles Darwin made many discoveries that led to the theory of evolution by natural selection while studying the plants and animals on these islands.

inherited traits Features that are passed from one generation to the next.

natural selection Results when some organisms have traits that make them better suited to live in a certain environment than others; they are more likely to survive, reproduce and pass their traits on to future generations than those without the special traits.

species A group of individuals that are genetically related and can breed to produce fertile young.

trait A feature or characteristic of an organism. For example, your height, hair color, and eye shape are physical traits.

Points to Consider

- Evolution by natural selection is supported by extensive scientific evidence. What do you think this evidence consists of?

7.2 Lesson 7.2: Evidence of Evolution

Lesson Objectives

- Understand that the scientific theory of biological evolution is based on extensive physical evidence and testing. This includes:
  - differences between fossils in different layers of rock
  - the age of rocks and fossils

- vestigial structures
- similarities between embryos of different organisms
- the same DNA and RNA materials found in all organisms
- similar genomes found in almost all organisms.

Check Your Understanding

- Where did Charles Darwin collect evidence of evolution and what kinds of evidence did he find?
- What is natural selection?
- What kinds of traits change through evolution?

Introduction

Though the idea of evolution had been proposed prior to Charles Darwin, most people think of Darwin's name when they think of evolution. Unlike others before him who based their ideas on speculation, opinions, myths, or folklore, Darwin's theories were based on a tremendous amount of scientific evidence.

In 1859, Charles Darwin and Alfred Russel Wallace first presented several forms of evidence of evolution. Their evidence included:

- fossils of extinct species from different eras
- similarities between the embryos of different species
- physical traits of different species
- the behavior of different species
- the distributions of different plant and animal species around the world.

Darwin and other 19^{th} century scientists came to the conclusions they did without knowing anything about molecular biology. Today, even more evidence of evolution by natural selection is coming from molecular biology and genetics. Genetics is also helping explain the mechanisms of how evolution occurs.

The Fossil Record

Paleontologists are the scientists who study fossils to learn about life in the past. **Fossils** are the preserved remains or traces of animals, plants, and other organisms from the distant past. Examples of fossils include bones, teeth, impressions, and leaves. Paleontologists compare the features of species from different periods in history. With this information, they try to unravel how species have evolved over millions of years (**Figure** 26.2). This

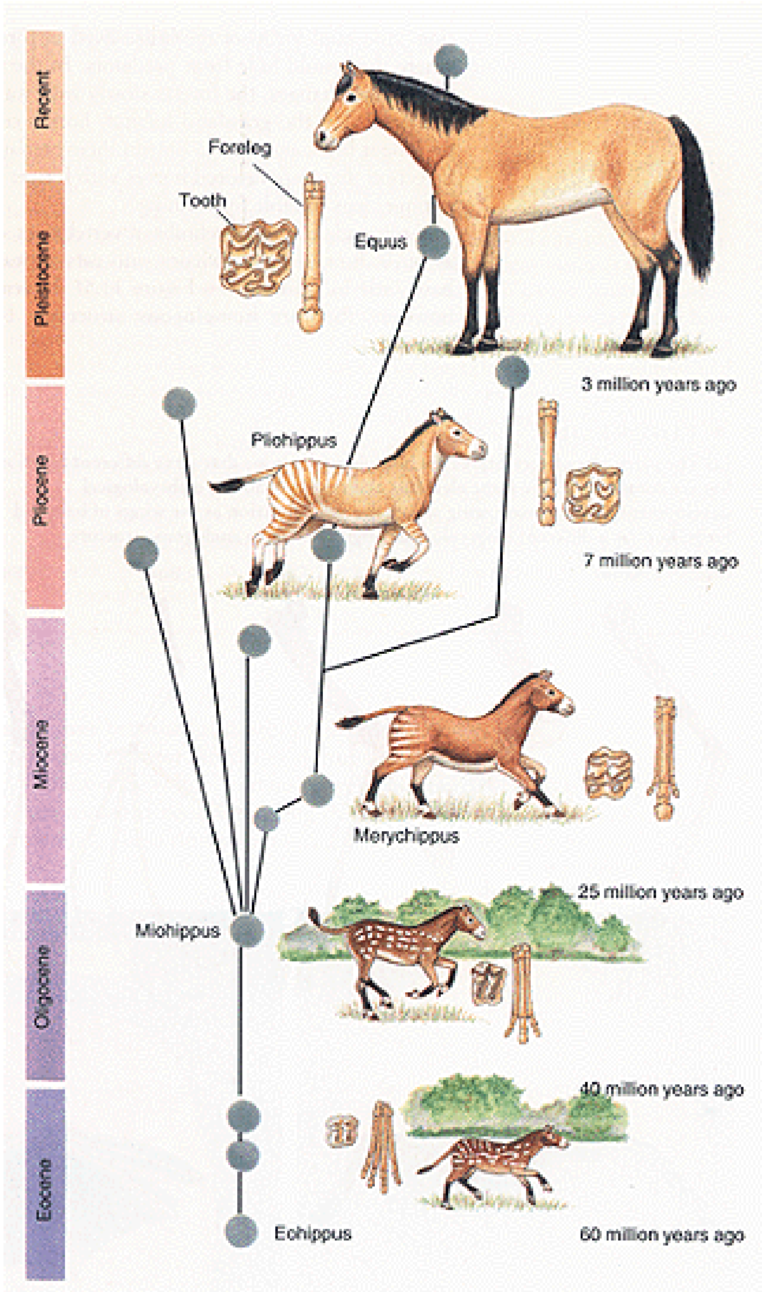

Figure 7.15: Evolution of the horse. Fossil evidence, depicted by the skeletal fragments, demonstrates evolutionary milestones in this process. Notice the 57 million year evolution of the horse leg bones and teeth. Especially obvious is the transformation of the leg bones from having four distinct digits to the hoof formation of today's horse. (3)

method works better with some species than others. For example, it is difficult to track the evolution of bacteria from fossils, because their single cells do not last well as fossils.

Until recently, fossils were the main source of evidence of evolution (**Figures** 7.16 and 7.17). The location of each fossil in layers of rocks provides clues to the age of the species and how species evolved in the past. Older materials and fossils are deeper in the earth; newer fossils and materials are closer to the surface.

Figure 7.16: A fossil is the remains of a plant or animal that existed some time in the distant past. Fossils, such as this one, were found in rocks or soil that was laid down long ago. (17)

Fossils and the rocks they are embedded in provide evidence of how life and environmental conditions have changed throughout Earth's history. They also help us understand how the past and present distribution of life on Earth is affected by earthquakes, volcanoes, and shifting seas, and other movements of the continents.

The Age of Rock Layers and Fossils

The many layers of sedimentary rock provide evidence of the long history of Eearth and the order of life forms whose remains are found in the rocks. The youngest layers are not always found on top, because of folding, breaking, and uplifting of layers. If the layers of earth were tilted by earthquakes or volcanoes, geologists can figure out which layers came from the deepest parts of the Earth.

The fossils and the order in which fossils appear is called the fossil record. This record provides important records of how species have evolved, divided and gone extinct. Methods used to date the age of rocks and fossils make it possible to determine when these events

Figure 7.17: About 40 to 60 million years ago this mosquito and fly were trapped in the gooey stuff, called resin that comes from trees. The fossils in the movie *Jurassic Park*, were trapped in resin. (14)

happened.

Geologist use a method called radiometric dating to determine the age of rocks and fossils in each layer of rock. This technique measures the decay rate of radioactive materials in each rock layer (**Figure** 7.18).

Radiometric dating has been used to determine that the oldest known rocks on Earth are between 4-5 billion years old. The oldest fossils are between 3-4 billion years old.

Vestigial Structures

Millions of species of animals, plants and microorganisms are alive today. Even though two different species may not look similar, they may have similar internal structures, and chemical processes that indicate they can have a common ancestor.

Some of the most interesting kinds of evidence for evolution are body parts that have lost their use through evolution (**Figure** 7.19). Most birds need their wings to fly. But the wings on an ostrich have lost their original use. These are called **vestigial structures**. Penguins do not use their wings to fly in the air; however they do use them to "fly" in the water. A whale's pelvic bones-which were once attached to legs- are also vestigial structures (**Figure** 7.20).

If you look at an x-ray of the bones in your back (called vertebrae), you will see several

Figure 7.18: This device, called a spectrophotometer can be used to measure the level of radioactive decay of certain elements in rocks and fossils to determine their age. (9)

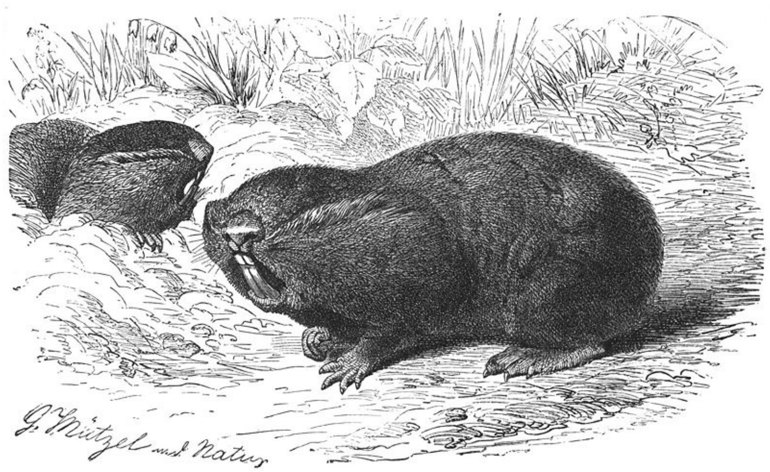

Figure 7.19: Mole rats live under ground where they do not need eyes to find their way around. This mole's eyes are covered by skin. Body parts that do not serve any function are vestigial structures. (22)

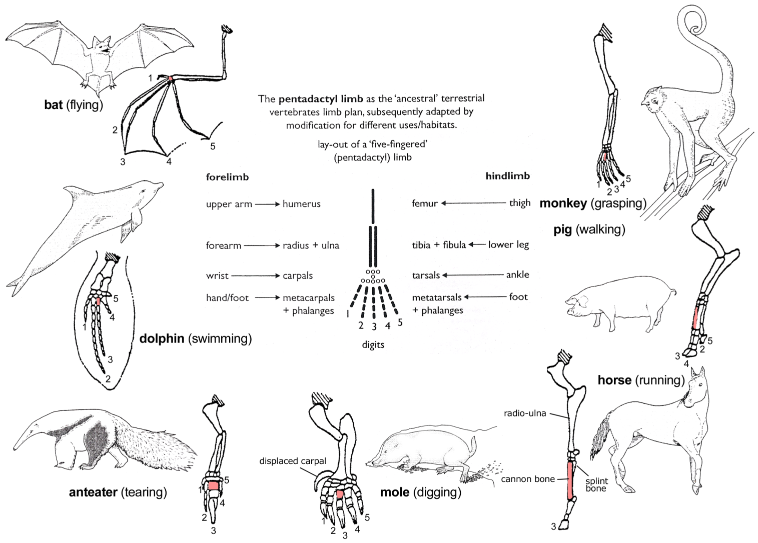

Figure 7.20: The bones in your arms and hands have the same bone pattern as those in the wings, legs, and feet of the animals pictured above. How have the bones adapted for different uses in each animal? (6)

vertebrae that come under your hips. These are called your tailbone. We do not use these small vertebrae; they are further evidence of our evolution.

Embryological Evidence

Some of the oldest evidence of evolution comes from embryology, the study of how organisms develop. An embryo is an animal or plant in its earliest stages of development, before it is born or hatched.

Centuries ago, people recognized that the embryos of many different species have similar appearances (**Figure** 7.21). The embryos of some species are even difficult to tell apart. Many of these animals do not differ much in appearance until they develop further. Many traits of one type of animal appear in the embryo of another type of animal. For example, fish embryos and human embryos both have gill slits. In fish they develop into gills, but in humans they disappear before birth (**Figure** 7.22).

The similarities between embryos suggests that these animals are related and have common ancestors. For example, humans did not evolve from chimpanzees. But the similarities between the embryos of both species may be due to our development from a common ancestor with chimpanzees. As our common ancestor evolved, both humans and chimpanzees developed different traits.

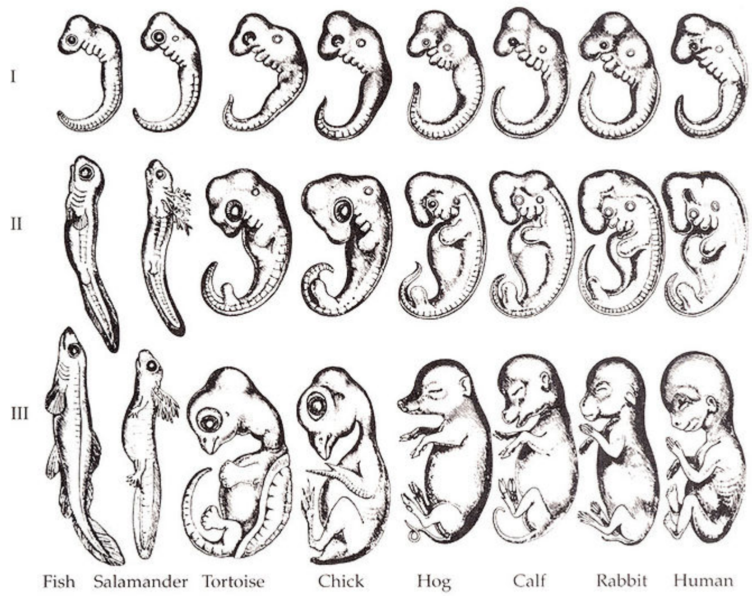

Figure 7.21: This drawing was made to show the similarities between the embryos of many species. Embryos of many different kinds of animals: mammals, birds, reptiles, fish, etc. look very similar. (36)

Figure 7.22: This is a six week old human embryo. Notice the similarities between this embryo and those of the other animals in figure 3. (33)

Similarities Between Molecules and Genomes

Molecular Clocks

Arguably, some of the most significant evidence of evolution comes from examining the molecules and DNA found in all organisms (**Figure** 7.23). The field of molecular biology did not emerge until the 1940s and has since confirmed and extended the conclusions about evolution drawn from other forms of evidence. **Molecular clocks** are used in molecular evolution to relate the time that two species diverged to the number of differences measured between the species' DNA sequences or protein amino acid sequences. These clocks are sometimes called gene clocks or evolutionary clocks. The fewer the differences the less time since the divergence of the species. For example, a chicken and a gorilla will have more differences between their DNA and protein amino acid sequences then a gorilla and an orangutan. This provides additional evidence that the gorilla and orangutan are evolutionally closer related than the gorilla and the chicken.

Molecular clocks, combined with other forms of evidence, such as evidence from the fossil record, has provided considerable evidence to estimate how long ago various groups of organisms diverged evolutionarily from one another.

Molecular Genetics

The development of molecular genetics has revealed the record of evolution left in the genomes of all organisms (**Figure** 7.24). It also provides new information about the relationships among species and how evolution occurs.

Molecular genetics provides evidence of evolution such as:

- the same biochemical building blocks – such as amino acids and nucleotides - are responsible for life in all organisms, from bacteria to plants and animals
- DNA and RNA determines the development of all organisms
- the similarities and differences between the genomes, the gene sequences of each species, reveal patterns of evolution.

Lesson Summary

- Fossil evidence, depicted by the skeletal fragments, demonstrates evolutionary milestones.
- Fossils and the rocks they are embedded in provide evidence of how life and environmental conditions have changed throughout Earth's history.
- The fossils and the order in which fossils appear is called the fossil record.

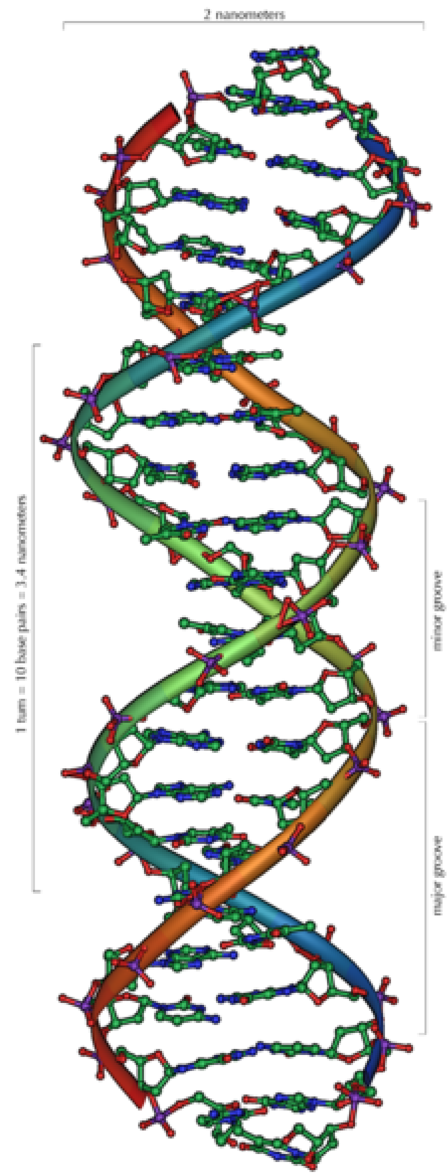

Figure 7.23: Almost all organisms are made from DNA with the same building blocks. The genomes (all of the genes in an organism) of all mammals are almost identical. (24)

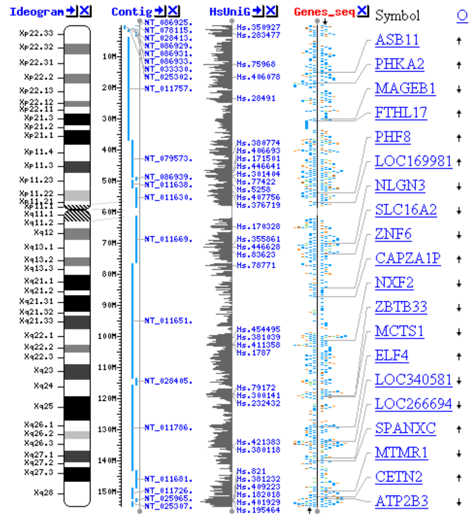

Figure 7.24: This is a map of the genes on just one of the 46 human chromosomes. Similarities and differences between the genomes (the genetic makeup) of different organisms reveal the relationships between the species. The human and chimpanzee genomes are almost identical- just about 1.2% differences between the two genomes. The complexity of the map signifies close evolutionary relationships when the genomes are highly similar. (13)

- Geologist use a method called radiometric dating to determine the age of rocks and fossils in each layer of rock.
- Radiometric dating has been used to determine that the oldest known rocks on Earth are between 4-5 billion years old. The oldest fossils are between 3-4 billion years old.
- Body parts that do not serve any function are called vestigial structures.
- Vestigial structures indicate that two species have a recent common ancestor.
- The similarities between embryos suggests that animals are related and have common ancestors.
- The same biochemical building blocks – such as amino acids and nucleotides - are responsible for life in all organisms, from bacteria to plants and animals.
- DNA and RNA determines the development of all organisms.
- The similarities and differences between the genomes, the gene sequences of each species, reveal patterns of evolution.

Review Questions

1. What are the different kinds of evidence of evolution?
2. How do geologists determine the age of rocks and fossils?
3. What is an embryo?
4. What is a vestigial structure?
5. What is an example of a vestigial structure?

6. What is a genome?
7. What is the most convincing evidence of evolution?
8. How do the embryos of different species support the idea of evolution?

Further Reading / Supplemental Links

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- http://en.wikipedia.org/

Vocabulary

embryo An animal or plant in its earliest stages of development, before it is born or hatched.

embryology The study of how organisms develop.

fossil The preserved remains or traces of animals, plants, and other organisms from the distant past; examples include bones, teeth, impressions, and leaves.

fossil record Fossils and the order in which fossils appear; provides important records of how species have evolved, divided and gone extinct.

genetics The scientific study of heredity.

genome All of the genes in an organism.

paleontologists Scientists who study fossils to learn about life in the past.

radiometric dating A method to determine the age of rocks and fossils in each layer of rock; measures the decay rate of radioactive materials in each rock layer.

vestigial structure Body part that has lost its use through evolution, such as a whale's pelvic bones.

Points to Consider

- How do you think new species evolve?
- How long do you think it takes for a new species to evolve?

7.3 Lesson 7.3: Macroevolution

Lesson Objectives

- Students will understand the differences between macroevolution and microevolution.
- Students will understand that speciation is the formation of new species.
- Students will understand the mechanisms of speciation.

Check Your Understanding

- Why can't an individual person evolve? Why can only groups evolve over many generations?
- What causes a species or a population to evolve?

Introduction

Small changes or large changes, how does evolution occur? It is easy to think that many small changes, as they accumulate over time, may gradually lead to a new species. Or is it possible that due to severe changes in the environment, large changes are needed to allow species to adapt to the new surroundings? Or are both probable methods of evolution?

Microevolution and Macroevolution

Microevolution

You already know that evolution is the change in species over time, due to the change of how often an inherited trait occurs in a population over many generations. Most evolutionary changes are small and do not lead to the creation of a new species. These small changes are called **microevolution**.

An example of microevolution is the evolution of pesticide resistance in mosquitoes. Imagine that you have a pesticide that kills most of the mosquitoes in your state one year. As a result, the only remaining mosquitoes are the pesticide resistant mosquitoes. When these mosquitoes reproduce the next year, they produce more mosquitoes with the pesticide resistant trait. This is an example of microevolution because the number of mosquitoes with this trait changed. However, this evolutionary change did not create a new species of mosquito, because the pesticide resistant mosquitoes can still reproduce with other mosquitoes if they were put together.

Macroevolution

Macroevolution refers to much bigger evolutionary changes that result in new species. Macroevolution may happen:

1. when many microevolution steps lead to the creation of a new species,
2. as a result of a major environmental change, such as volcanic eruptions, earthquakes or an asteroid hitting Earth, which changes the environment so much that natural selection leads to large changes in the traits of a species.

After thousands of years of isolation from each other, some of Darwin's finch population, which was discussed in the *Evolution by Natural Selection* lesson, will not or cannot breed with other finch populations when they are brought together. Since they do not breed together, they are classified as separate species.

Genotype or Phenotype?

Natural selection acts on the phenotype - the traits or characteristics - of an individual, not on the underlying genotype. For many traits, the homozygous genotype, AA for example, has the same phenotype as the heterozygous Aa genotype. If both an AA and Aa individual have the same phenotype, the environment cannot distinguish between them. So natural selection cannot choose a homozygous individual over a heterozygous individual. If homozygous recessive aa individuals are selected against, that is they are not well adapted to their environment, acting on the phenotype allows the *a* allele to be maintained in the population through heterozygous *Aa* individuals.

Carriers

Because natural selection acts on the phenotype, if an allele is lethal in a homozygous individual, *aa* for example, it will not be lethal in a heterozygous *Aa* individual. These heterozygous *Aa* individuals will then act as carriers of the *a* allele. This allele is then maintained in the population's gene pool. The gene pool is the complete set of alleles within a population.

Tay-Sachs disease is an autosomal recessive genetic disorder. It is caused by a genetic defect in a single gene with one defective copy of that gene inherited from each parent, *rr* for example. Affected individuals usually die from complications of the disease in early childhood. Affected individuals must have unaffected parents, each being a carrier of the defective allele, so the parents are heterozygous *Rr*. This lethal allele is maintained in the gene pool through these unsuspecting heterozygous individuals; they do not show any symptoms of the disease, so most individuals do not get tested to see if they are carriers.

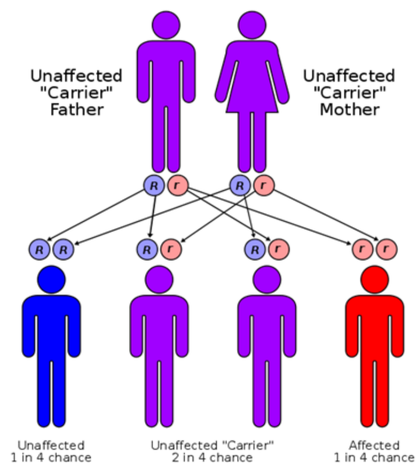

Figure 7.25: Tay-Sachs disease is inherited in the autosomal recessive pattern. Each parent is an unaffected carrier of the lethal allele. (37)

Hardy-Weinberg Equilibrium

The Hardy-Weinberg model (sometimes called a law) states that a population will remain at **genetic equilibrium** - with constant (unchanging) allele and genotype frequencies and no evolution - as long as five conditions are met:

1. No mutation (no change in the DNA sequence)
2. No migration (no moving into or out of a population)
3. Very large population size
4. Random mating (mating not based on preference)
5. No natural selection.

These five conditions rarely occur in nature. For example, it is highly unlikely that new mutations are not constantly generated. If these five conditions are met, the frequencies of genotypes within a population can be determined given the phenotypic frequencies.

The Hardy-Weinberg Equation

For example, let's use a hypothetical rabbit population of 100 rabbits (200 alleles) to determine allele frequencies for color:

- 9 albino rabbits (represented by the alleles bb) and
- 91 brown rabbits (49 homozygous [BB] and 42 heterozygous [Bb]).

The gene pool contains 140 B alleles [49 + 49 + 42] (70%) and 60 b alleles [9 + 9 + 42] (30%) – which have gene frequencies of 0.7 and 0.3, respectively.

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:

- BB: 0.7 x 0.7 = 0.49
- Bb: 0.7 x 0.3 = 0.21
- bB: 0.3 x 0.7 = 0.21
- bb: 0.3 x 0.3 = 0.09

If we calculate the frequency of genotypes among the offspring, they are identical to the genotype frequencies of the parents. There are 9% bb albino rabbits and 91% BB and Bb brown rabbits. 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 (so **p** + **q** must equal 1), but similar equations can be written for more alleles.

Allele frequency equals the chance of any particular gamete receiving that allele. Therefore, when egg and sperm combine, the probability of any genotype is the product of the probabilities of the alleles in that genotype. So:

Probability of genotype ***BB*** = ***p*** X ***p*** = $\mathbf{p}^2$ and

Probability of genotype ***Bb***= (***p*** X ***q***) + (***q*** X ***p***) = **2pq** and

Probability of genotype ***bb*** = ***q*** X ***q*** = $\mathbf{q}^2$

We have included all possible genotypes, so the probabilities must add to 1.0. In our example 0.49 + 2(0.21) + 0.9 = 1. Our equation becomes:

Table 7.1:

$\boldsymbol{p^2}$	+	**2** ***pq***	+	$\boldsymbol{q^2}$	=	**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.

Genetic Drift

Recall that the third requirement for Hardy-Weinberg equilibrium is a very large population size. This is because variations in allele frequencies that occur by chance are minimal in large populations. In small populations, random variations in allele frequencies can significantly influence the "survival" of any allele. Random changes in allele frequencies in small populations is known as **genetic drift.** As the population (and therefore the gene pool) is small, genetic drift could have substantial effects on the traits and diversity of a population. Many biologists think that genetic drift is a major cause of microevolution.

The Origin of Species

The creation of a new species is called **speciation**. Most new species develop naturally, but humans have also artificially created new subspecies, breeds, and species for thousands of years.

Natural selection causes beneficial heritable traits to become more common in a population, and unfavorable heritable traits become less common. For example, a giraffe's neck is beneficial because it allows the giraffe to reach leaves high in trees. Natural selection caused this beneficial trait to become more common than short necks.

As new mutations (changes in the DNA sequence) are constantly being generated in a population's gene pool, some of these mutations will be beneficial and result in traits that allow adaptation and survival. Natural selection causes evolution through the genetic change of a species as the beneficial traits become more common within a population.

Artificial selection is when humans select which plants or animals to breed to pass specific traits on to the next generation. A farmer may choose to breed only the cows that produce the best milk (the favored traits) and not breed cows that do not produce much milk (a less desirable trait). Humans have also artificially breed dogs to create new breeds (**Figure** 7.26).

Figure 7.26: Artificial Selection: Humans used artificial selection to create these different breeds. Both dog breeds are descended from the same wolves, and their genes are almost identical. Yet there is at least one difference between their genes that determine size. (8)

Reproductive Isolation

There are two main ways that speciation happens naturally. Both processes create new species by isolating groups (populations) of the same species from each other. Organisms can be reproductively isolated from each other either geographically or by some behavior. Over long period of time (usually thousands of years), each population evolves in a different direction. One way scientists test whether two populations are separate species is to bring them together again. If the two populations do not interbreed and produce fertile offspring, they are separate species.

Geographic Isolation

Allopatric speciation happens when groups from the same species are geographically isolated physically for long periods. Imagine all the ways that plants or animals could be isolated from each other:

- a mountain range
- a canyon water such as rivers, streams, or an ocean
- a desert

Charles Darwin recognized that speciation could happen when some members of a species were isolated from the others for hundreds or thousands of years. Darwin had observed thirteen distinct finch species on the Galápagos Islands that had evolved from the same ancestor. Several of the finch population evolved into separate species while they were isolated on separate islands. Scientists were able to determine which finches had evolved into distinct species by bringing members of each population together. The birds that would not or could not interbreed are regarded as separate species.

A classic example of geographic isolation is the Abert squirrel, shown in **Figures** 7.27) and 7.28). When the Grand Canyon in Arizona formed, squirrels from one species were separated by the giant canyon that they could not cross. After thousands of years of isolation from each other, the squirrel populations on the northern wall of the canyon looked and behaved differently from those on the southern wall. North rim squirrels have white tails and black bellies. Squirrels on the south rim have white bellies and dark tails.

Isolation without Physical Separation

Sympatric speciation happens when groups from the same species stop interbreeding, because of something other than physical separation, such as behavior. The separation may be due to different mating seasons, for example. Sympatric speciation is more difficult to identify.

Some scientists suspect that two groups of orcas (killer whales) live in the same part of the Pacific Ocean part of the year, but do not interbreed. The two groups hunt different prey species, eat different foods, sing different songs, and have different social structures.

Different behaviors may have also led to the emergence of two Galápagos finch species that live in the same space. The two species are separated by behavioral barriers such as mating

Figure 7.27: Abert Squirrel on the southern rim of the Grand Canyon (26)

signals. In this case, members of each group select mates according to different beak structures and bird calls. They do not need physical barriers, because behavioral differences do enough to keep the groups separated.

Allopatric speciation and sympatric speciation are both forms of **reproductive isolation**. Allopatric speciation is due to **geographic isolation**. Sympatric speciation is due to **behavioral isolation**, or isolation due to different mating seasons, which is also known as **temporal isolation**.

Rates of Evolution

How fast is evolution? How long did it take for the giraffe to develop a long neck? How long did it take for the Galápagos finches to evolve? How long did it take for whales to evolve from land mammals? These and other questions about the rate of evolution are difficult to answer, but evidence does exist in the fossil record.

The rate of evolution is a measurement of the speed of evolution. Genetically speaking, evolution is how much an organism's genotype (the genes that make up an individual) changes over a set period of time. Evolution is usually so gradual that we do not see the change for many, many generations. Humans took millions of years to evolve from a mammal that is now extinct.

Not all organisms evolve at the same rate. It would be difficult to measure evolution on your family because you are only looking at a small population over a few generations. However

Figure 7.28: Kaibab squirrel (a subspecies of Abert's) found on northern rim of the Grand Canyon (19)

there are organisms that are evolving so fast that you may be able to observe evolution! Many scientists use bacteria or other species that reproduce frequently to study evolution. Species with short life cycles and that reproduce frequently evolve much faster than others. Bacteria evolve hundreds (or thousands or more) of times faster than humans do. Bacteria go through so many generations in a few days, that we can actually witness evolution. A human takes about 22 years to go through one generation. But some bacteria go through over a thousand generations in less than two months.

Evolutionary Trees

Charles Darwin came up with the idea of an evolutionary tree to represent the relationships between different species and their common ancestors (**Figure** 7.29). The base of the tree represents the ancient ancestors of all life. The separation into large branches shows where these original species evolved into increasingly different populations that would not come back together again. The branches keep splitting into smaller and smaller branches as species continue to evolve into more and more species. Some species are represented by short twigs spurting out of the tree, then stopping. These are species that went extinct before evolving into new species. Other "Trees of Life" have been created by other scientists (**Figure** 7.30).

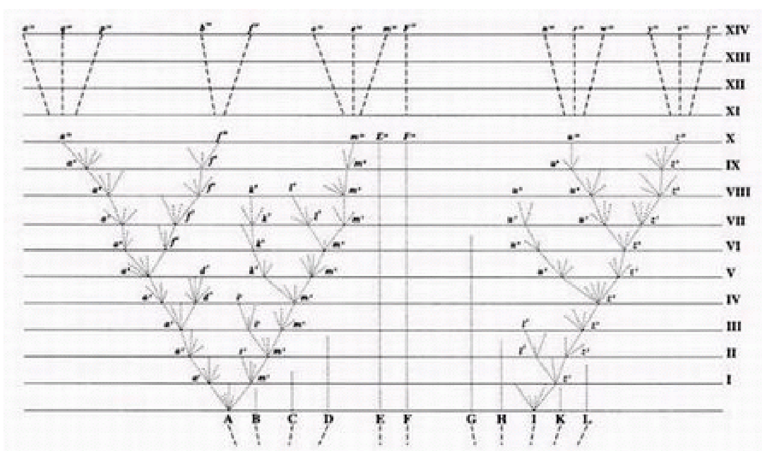

Figure 7.29: Darwin drew this version of the "Tree of Life" to represent how species evolve and diverge into separate directions. Each point on the tree where one branch splits off from another represents the common ancestor of the species on the separate branches. (25)

Theory?

Darwin's Theory of Evolution by Natural Selection is supported by well over 150 years of scientific evidence, ranging from fossil evidence to DNA evidence. By definition, this is a well tested scientific theory. An abundance of scientific evidence supports this theory. The

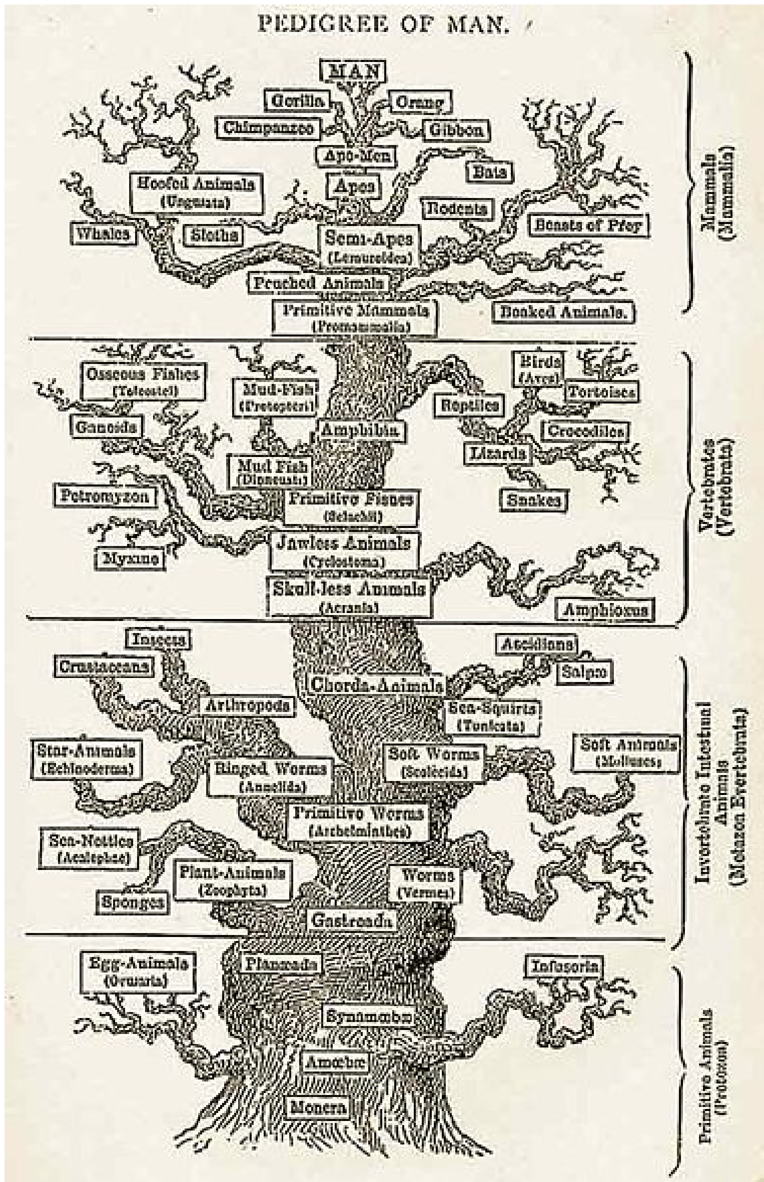

Figure 7.30: Scientists have drawn many different versions of the "Tree of Life" to show different features of evolution. This "Tree of Life" was made by Ernst Haeckel in 1879. (5)

world is very old and has undergone some dramatic changes. Life has been on the planet for most of that time. As you will see in the next lesson, life started as single celled organisms and has evolved over billions of years into complex plants and animals. But this journey has not been easy. Most species that have ever lived are now extinct. There have been a number of mass extinctions, where many species vanished all at once. It is because of the tremendous diversity of species that has allowed some to adapt to whatever changes nature throws in its path, from small changes to major environmental disturbances. So it is nature that selects - hence *Natural Selection* - which species adapts, survives and evolves.

Lesson Summary

- Microevolution results from evolutionary changes that are small and do not lead to the creation of a new species.
- Macroevolution refers to large evolutionary changes that result in new species.
- Macroevolution may happen when many microevolution steps lead to the creation of a new species.
- Macroevolution may happen as a result of a major environmental change, such as volcanic eruptions, earthquakes or an asteroid hitting Earth, which changes the environment so much that natural selection leads to large changes in the traits of a species
- The creation of a new species is called speciation.
- Natural selection causes beneficial heritable traits to become more common in a population, and unfavorable heritable traits become less common.
- Artificial selection is when humans select which plants or animals to breed to pass specific traits on to the next generation.
- Allopatric speciation occurs when groups from the same species are geographically isolated physically for long periods.
- Sympatric speciation occurs when groups from the same species stop interbreeding, because of something other than physical separation, such as behavior.
- Allopatric speciation and sympatric speciation are both forms of reproductive isolation.
- The rate of evolution is a measurement of the speed of evolution. Genetically speaking, evolution is how much an organism's genotype changes over a set period of time.
- Not all organisms evolve at the same rate.
- Evolutionary trees are used to represent the relationships between different species and their common ancestors.

Review Questions

1. What is the difference between macroevolution and microevolution?
2. What conditions cause organisms to evolve and adapt?
3. What do the branches on the Tree of Life represent?
4. Which organism has a faster rate of evolution: a human or a bacterium?

5. How do you know if two related organisms are members of the same species?
6. Why do the squirrels on opposite side of the Grand Canyon look different?
7. How is artificial selection different from natural selection?
8. What, other than physical isolation, could cause a species to split into two different directions of evolution?

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Vocabulary

allopatric speciation Speciation that occurs when groups from the same species are geographically isolated physically for long periods.

artificial selection Occurs when humans select which plants or animals to breed to pass specific traits on to the next generation.

behavioral isolation The separation of a population from the rest of its species due to some behavioral barrier, such as having different mating seasons.

evolutionary tree Diagram used to represent the relationships between different species and their common ancestors.

genotype The genes that make up an individual.

geographic isolation The separation of a population from the rest of its species due to some physical barrier, such as a mountain range, an ocean, or great distance.

macroevolution Big evolutionary changes that result in new species.

microevolution Small changes in inherited traits; does not lead to the creation of a new species.

natural selection Causes beneficial heritable traits to become more common in a population, and unfavorable heritable traits become less common.

primate A group of related mammal species that have binocular vision, specialized hands and feet for grasping, and enlarged and differentiated brains; includes humans, chimpanzees, the apes, monkeys, and lemurs.

reproductive isolation allopatric and sympatric speciation; isolation due to geography or behavior, resulting in the inability to reproduce.

speciation The creation of a new species; either by natural or artificial selection.

sympatric speciation Speciation that occurs when groups from the same species stop interbreeding, because of something other than physical separation, such as behavior.

temporal isolation Isolation due to different mating seasons.

Points to Consider

- How long do you think humans have been around?
- How long do you think Earth existed before life formed?
- For how much of Earth's history have humans existed?

7.4 Lesson 7.4: History of Life on Earth

Lesson Objectives

- Know that geologists and paleontologists use evidence to determine the history of Earth and life on Earth.
- Know that geologists and paleontologists measure the radioactivity in certain rocks to determine the age of the earth and fossils.
- Know that the earth is between four and five billion years old.
- Know that scientists need to know what the environment (what chemicals were around, the temperature, etc.) was like on Earth billions of years ago to know how life formed.

Check Your Understanding

- What are fossils?
- How does the fossil record contribute to the evidence of evolution?

Introduction

It is no surprise that people have wondered about the age of the earth, how it was formed, and how life began on Earth for hundreds, even thousands, of years. Try to imagine how ancient philosophers tried to explain the history of the earth and life. Many people used mythology or cultural beliefs to explain elaborate stories about how and when the earth formed.

The past two to three hundred years has been an exciting time for geologists, paleontologists and other scientists who are trying to trace the history of the earth. What was once a hobby, studying land forms and fossils has become a science that is revealing the history of the earth and life on Earth.

Age of Earth

During the 1800s, geologists, paleontologists and naturalists found several forms of physical evidence that confirmed that the earth is very old, far older than the 6,000 years that some leaders had claimed. Their evidence included:

- Fossils of ancient sea life on dry land far from oceans: This supported the idea that the earth changed over time and that some dry land today was once covered by oceans.
- The many layers of rock: When people realized that rock layers represent the order in which rocks and fossils appeared, they were able to start to trace the history of the earth and life on Earth.
- Indications that volcanic eruptions, earthquakes and erosion that happened long ago shaped much of the earth's surface. This supported the idea of an older Earth.

Radiometric Dating

During the past one hundred years, geologists and paleontologists have been able to delve even deeper into the earth's history with new tools of science. The most convincing method, called **radiometric dating**, was developed more than one hundred years ago. Rocks are made up of minerals. Scientists found that they could measure the age of rocks by measuring the radioactivity of certain minerals in rocks. Geologists and paleontologists still use variations of radiometric dating to determine the age of fossils and rocks today (**Figure** 7.31).

Figure 7.31: The most reliable way to figure out the earth's age is to measure the radioactivity of certain minerals found in rocks (called radiometric dating). This mass spectrophotometer can also be used to measure age of fossils from the level of radiation in minerals surrounding the fossil. (1)

Over 4 Billion Years

The earth is at least as old as its oldest rocks. The oldest rock minerals found on Earth so far are zircon crystals that are at least 4.404 billion years old. These tiny crystals were found in the Jack Hills of Western Australia. Since the earth is at least as old as the oldest minerals found on Earth, geologists estimate that the minimum age of the earth is 4.404 billion years.

Likewise, the earth cannot be any older than the solar system. The oldest possible age of the earth is 4.57 billion years old, the age of the solar system. Geologists and geophysicists based the age of the universe on the age of materials within meteorites that are formed within the solar system.

Origin of Life on Earth

There is good evidence that life has probably existed on Earth for most of Earth's history. Some of the oldest fossils of life forms on Earth are at least 3.5 billion year old fossils of blue green algae found in Australia (**Figure** 7.32).

The next step is to determine exactly how life formed billions of years ago. First, scientists need to know what the environment was like 3.5 to 4 billion years ago; they need to know

Figure 7.32: Some of the oldest fossils on earth are stromolites, made of algae and a kind of bacteria, found along the coast of Australia. (11)

what kinds of materials were available then that could have been involved in the creation of life. Scientists believe the early earth contained no oxygen gas, but did contain other gases, including nitrogen, carbon dioxide, carbon monoxide, water vapor, hydrogen sulfide and probably a few others.

Life from Random Reactions

Today, we have evidence that life on Earth came from random reactions between chemical compounds that formed molecules; in a series of random steps, these molecules created proteins and nucleic acids (RNA or DNA), and then cells. We know that the ingredients for life (the building blocks of life), were present at the beginning of Earth's history. Some chemicals were in water and volcanic gases. Other chemicals would have come from meteorites in space. Energy to drive chemical reactions was provided by volcanic eruptions and lightening. Keep in mind that this process may have taken as much as 1 billion years. Our understanding of how life originated on Earth is developing gradually (**Figure** 7.33).

Figure 7.33: Some clues to the origins of life on Earth come from studying the early life forms that developed in hot springs, such as the Grand Prismatic Spring at Yellowstone National Park. This spring is approximately 250 feet by 300 feet wide. (38)

Geologic Time Scale

Geologists and other earth scientists use geologic time scales to describe when events occurred throughout the history of Earth. The time scales can be used to illustrate when both geologic events and events affecting plant and animal life occurred. All of the earth events we see happening today, such as earthquakes, volcanic eruptions, and erosion, have happened throughout history. Past catastrophic events, such as asteroids and comets also hit the earth long before humans evolved.

The geologic time scale in **Figure** 7.34 illustrates the timing of events such as:

- earthquakes
- volcanic eruptions
- major erosion
- meteorites hitting Earth
- the first signs of life forms
- mass exterminations

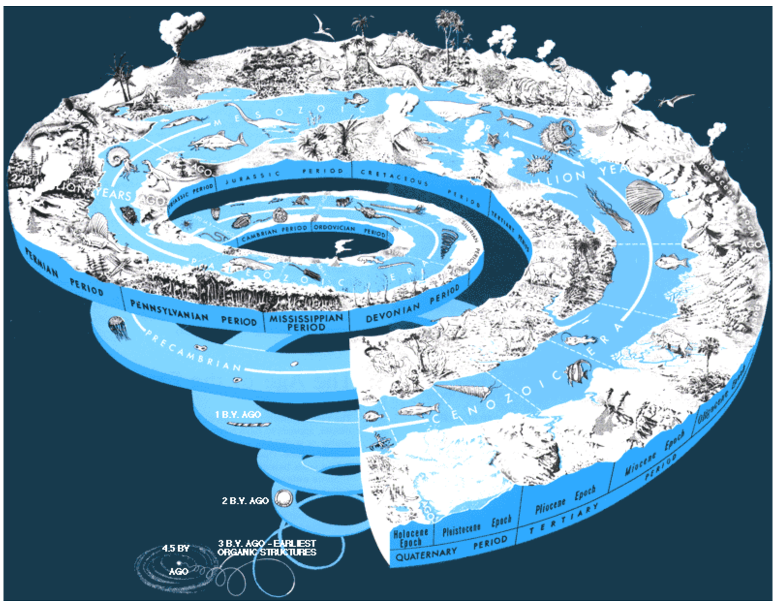

Figure 7.34: The geological time scale of Earth's past is organized according to events which took place during different periods on the time scale. Geologic time is the same as the age of the earth: between 4.04 and 4.57 billion years. Look closely for such events as the extinction of dinosaurs and many marine animals. (10)

Evolution of Major Life Forms

Life on Earth began about 3.5 to 4 billion years ago. The first life forms were single cell organisms, prokaryotic organisms, similar to bacteria. The first multicellular organisms did not appear until about 610 million years ago in the oceans. These of course would be eukaryotic organisms. Some of the first multicellular forms included sponges, brown algae, and slime molds.

Many of the modern types of organisms we know today evolved during the next ten million years in an event called the Cambrian explosion. This sudden burst of evolution may have been triggered by some environmental changes that made the environment more suitable for a wider variety of life forms.

Plants and fungi did not appear until roughly 500 million years ago. They were soon followed by arthropods (insects and spiders). Next came the amphibians about 300 million years ago, followed by mammals around 200 million years ago and birds around 100 million years ago.

Even though large life forms have been very successful on Earth, most of the life forms on Earth today are still prokaryotes – small, single celled organisms. Fossils indicate that many organisms that lived long ago are extinct. Extinction of species is common; in fact, it is estimated that 99% of the species that have lived on the earth no longer exist.

The basic timeline of Earth is a 4.6 billion year old Earth, with (very approximately):

- about 3.5 - 3.8 billion years of simple cells (prokaryotes)
- 3 billion years of photosynthesis
- 2 billion years of complex cells (eukaryotes)
- 1 billion years of multicellular life
- 600 million years of simple animals
- 570 million years of arthropods (ancestors of insects, arachnids and crustaceans)
- 550 million years of complex animals
- 500 million years of fish and proto-amphibians
- 475 million years of land plants
- 400 million years of insects and seeds
- 360 million years of amphibians
- 300 million years of reptiles
- 200 million years of mammals
- 150 million years of birds
- 130 million years of flowers
- 65 million years since the non-avian dinosaurs died out
- 2.5 million years since the appearance of *Homo*
- 200,000 years since humans started looking like they do today
- 25,000 years since *Neanderthals* died out

Mass Extinctions

Extinctions are part of natural selection. Species often go extinct when their environment changes and they do not have the traits they need to survive. Only those individuals with the traits needed to live in a changed environment survive (**Figure** 7.35).

Mass extinctions, such as the extinction of dinosaurs and many marine mammals, happened after major catastrophes such as volcanic eruptions and major earthquakes changed the

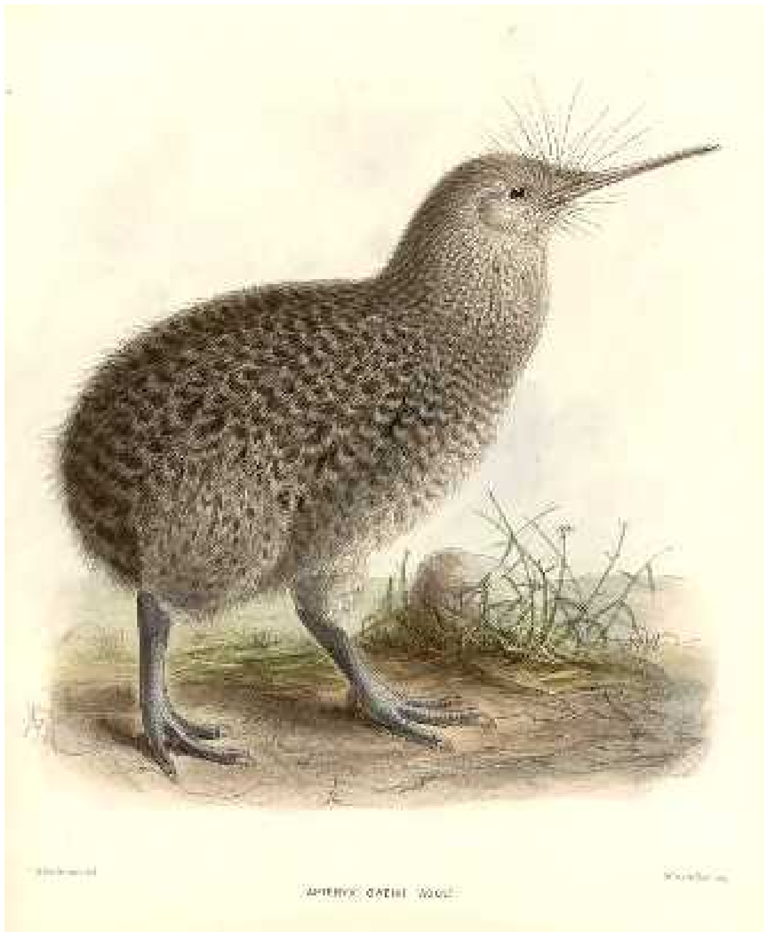

Figure 7.35: Humans have caused many extinctions by introducing species to new places. For example, many of New Zealand's birds have adapted to nesting on the ground. This was possible because there were no land mammals in New Zealand until Europeans arrived and brought cats, fox and other predators with them. Several of New Zealand's ground nesting birds, such as this flightless kiwi, are now extinct or threatened because of these predators. (28)

environment. Scientists have been looking for evidence of why dinosaurs went extinct over fairly short periods. Many scientists are examining the theory that a major cataclysmic events, such as an asteroid colliding with Earth, may have caused the extinction of dinosaurs 65 million years ago (**Figure** 7.36).

Figure 7.36: The fossil of Tarbosaurus, one of the land dinosaurs that went extinct during one of the mass extinctions. (21)

Since life began on Earth, there have been several major mass extinctions. If you look closely at the geological time scale, you will find that at least five major massive extinctions have occurred in the past 540 million years. In each mass extinction, over 50% of animal species died. The total number of extinctions could be as high as 20 mass extinctions during this period.

The fossil record tells the story of these mass extinctions: 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. Two specific extinctions occurred at the end of the Permian period and when the dinosaurs went extinct.

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 the supercontinent 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 smaller shoreline contributed to the dramatic loss of species, for up to 95% of marine species perished, compared to "only" 70% of land species. Although the exact cause remains unknown, fossils clearly document the fact of Earth's most devastating extinction.

Figure 7.37: 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. (16)

The dramatic extinction of all dinosaurs (except those which led to birds) marked the end of the Cretaceous period. A worldwide iridium-rich layer, dated at 65.5 million years ago, provides evidence for a dramatic cause for their ultimate extinction. Iridium is rare in the Earth's crust, but common in comets and asteroids. Scientists associate 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 decrease in food chains, leading to the extinction of the dinosaurs. The fossil record obviously depicts the presence of dinosaurs on Earth, and the absence of dinosaur fossils after this extinction event demonstrates the relationship between the fossil record and evolution.

Figure 7.38: The fossil record demonstrates the presence of dinosaurs, which went extinct over 65 million years ago. (39)

After each mass extinction, open ecological niches are quickly filled by other species. This is well documented in the fossil record. This episodic speciation following an event such as a mass extinction also shows the relationship between evolution and the fossil record.

Lesson Summary

- During the 1800s, geologists, paleontologists and naturalists found several forms of physical evidence that confirmed that the earth is very old.

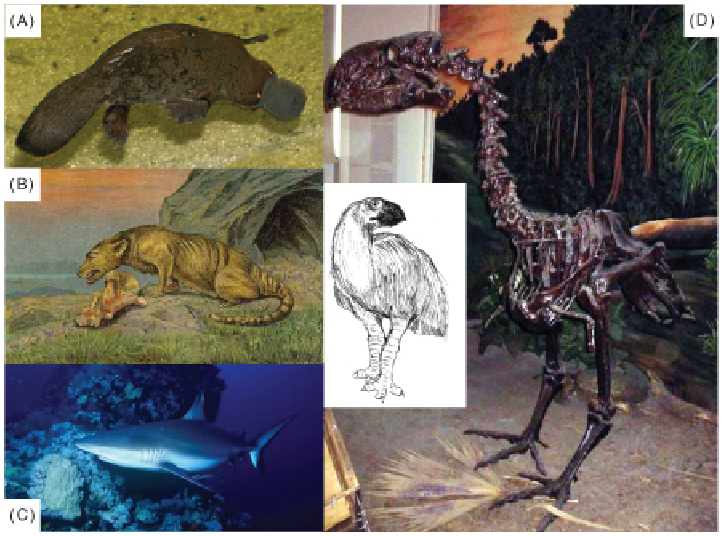

Figure 7.39: Mammals and birds quickly invaded ecological niches formerly occupied by the dinosaurs. Mammals included monotremes (A), marsupials, and hoofed placentals (B). Modern sharks (C) patrolled the seas. Birds included the giant flightless *Gastornis* (D). (34)

- Fossils of ancient sea life on dry land far from oceans supported the idea that the earth changed over time and that some dry land today was once covered by oceans.
- The many layers of rock represent the order in which rocks and fossils appeared.
- Indications that volcanic eruptions, earthquakes and erosion that happened long ago shaped much of the earth's surface.
- Radiometric dating allows scientists to measure the age of rocks by measuring the radioactivity of certain minerals in rocks.
- The oldest rock minerals found on Earth so far are zircon crystals that are at least 4.404 billion years old.
- Some of the oldest fossils of life forms on Earth are at least 3.5 billion year old fossils of blue green algae found in Australia.
- Scientists believe the early earth contained no oxygen gas, but did contain other gases, including nitrogen, carbon dioxide, carbon monoxide, water vapor, hydrogen sulfide and probably a few others.
- Geologists and other earth scientists use geologic time scales to describe when events occurred throughout the history of Earth.
- The geological time scale of Earth's past is organized according to events which took place during different periods on the time scale.
- Life on Earth began about 3.5 to 4 billion years ago.
- The first life forms were single cell organisms, prokaryotic organisms, similar to bacteria.
- The first multicellular organisms did not appear until about 610 million years ago in

the oceans. Some of the first multicellular forms included sponges, brown algae, and slime molds.
- Plants and fungi appeared roughly 500 million years ago. They were soon followed by arthropods (insects and spiders).
- Amphibians evolved about 300 million years ago, followed by mammals around 200 million years ago and birds around 100 million years ago.
- Extinction of species is common; in fact, it is estimated that 99% of the species that have lived on the earth no longer exist.
- Mass extinctions, such as the extinction of dinosaurs and many marine mammals, happened after major catastrophes such as volcanic eruptions and major earthquakes changed the environment.
- There have been at least five major massive extinctions have occurred in the past 540 million years.
- In each mass extinction, over 50% of animal species died.

Review Questions

1. How do scientists determine the age of a rock or fossil today?
2. How do we know the maximum possible age of the Earth?
3. How do we know the minimum possible age of the Earth?
4. How old is the Earth, based on current evidence?
5. Why is it difficult to determine how life started on Earth?
6. How long ago did life start on Earth?
7. When did mammals first appear on Earth?
8. What kinds of events are recorded on a geological time scale?

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Vocabulary

Cambrian explosion A sudden burst of evolution that may have been triggered by some environmental changes that made the environment more suitable for a wider variety of life forms.

extinct Something that does not exist anymore; a group of organisms that has died out without leaving any living representatives.

mass extinction An extinction when many species go extinct during a relatively short period of time.

radiometric dating A method to determine the age of rocks and fossils in each layer of rock; measures the decay rate of radioactive materials in each rock layer.

stromolites Fossils made of algae and a kind of bacteria; some of the oldest fossils on Earth.

Points to Consider

The next chapter focuses on prokaryotic organisms. Remember, prokaryotes lived on this planet for two billion years before eukaryotic cells even existed.

- Discuss with your class what you think are some of the characteristics, and some of the differences, of prokaryotic organisms.

Image Sources

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Chapter 8

Prokaryotes

8.1 Lesson 8.1: Bacteria

Lesson Objectives

- Describe the cellular features of bacteria.
- Explain the ways in which bacteria can obtain energy.
- Explain how bacteria reproduce themselves.
- Identify some ways in which bacteria can be helpful.
- Identify some ways in which bacteria can be harmful.

Check Your Understanding

- How do prokaryotic and eukaryotic cells differ?

Answer: Eukaryotic cells have a membrane-bound nucleus while prokaryotes do not.

- What are some components of all cells, including bacteria?

Answer: cell membrane, cytoplasm, etc.

Introduction

About 3.5 billion years ago, long before the first plants, people, or other animals appeared, prokaryotes were the first life forms on Earth. Recall that **prokaryotes** are single-celled organisms that lack a nucleus, and that the prokaryotes include bacteria and archaea. For at least a billion years, Bacteria and Archaea ruled the Earth as the only existing organisms. Even though life is much more diverse on Earth today, bacteria (singular: bacterium) are still the most abundant organisms on Earth. You probably know bacteria as "germs" that cause disease, but as you will see, they can also do many helpful things for the environment and humankind.

Characteristics of Bacteria

Bacteria are so small that they can only be visualized with a microscope. When viewed under the microscope, they have three distinct shapes. These three shapes allow bacteria to be classified by their shape. The **bacilli** are rod-shaped, the **cocci** are sphere-shaped, and the **spirilli** are spiral-shaped (**Figures** 8.1, 8.2 and 8.3).

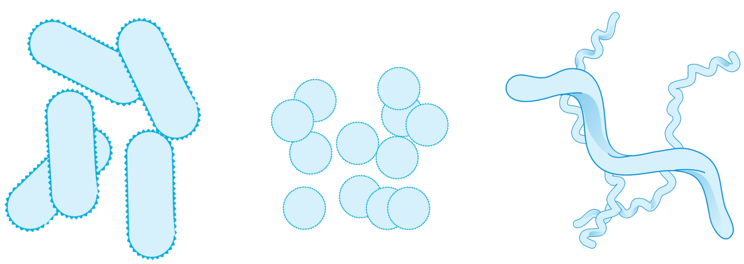

Figure 8.1: Bacteria come in many different shapes. Some of the most common shapes are bacilli (rods), cocci (spheres), and spirilli (spirals). Bacteria can be identified and classified by their shape. (7)

Bacteria are surrounded by a cell wall consisting of **peptidoglycan**, a complex molecule consisting of sugars and amino acids. The cell wall is important for protecting the bacteria. In fact the cell wall is so important that some antibiotics, such as penicillin, work to kill bacteria by preventing the proper synthesis of the cell wall. In parasitic bacteria, which depend on a host organism for energy and nutrients, capsules or slime layers surround the cell wall help defend against the host's defenses.

Recall that all prokaryotes, including the bacteria, lack the membrane-bound organelles and nucleus of eukaryotic cells (**Figure** 8.4). Like eukaryotic cells, however, prokaryotic cells do have cytoplasm, the fluid inside the cell; a plasma membrane, which acts as another barrier; and ribosomes, where proteins are assembled. The DNA of bacteria is mostly contained in a large circular strand, forming a single chromosome, that is compacted into a structure called the **nucleoid.** Many bacteria also have additional small rings of DNA known as **plasmids.**

Some bacteria also have tail-like structures called *flagella* (**Figure** 8.5). The flagella assist the bacteria with movement. As the flagella rotate, they spin the bacteria and propel them

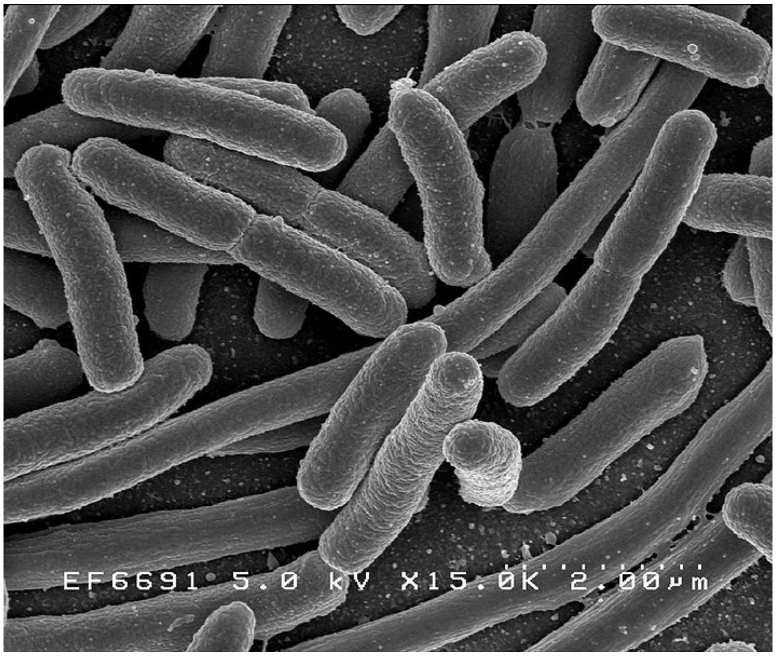

Figure 8.2: *Escherichia coli* is an example of bacteria that are rod-shaped, or bacilli. (2)

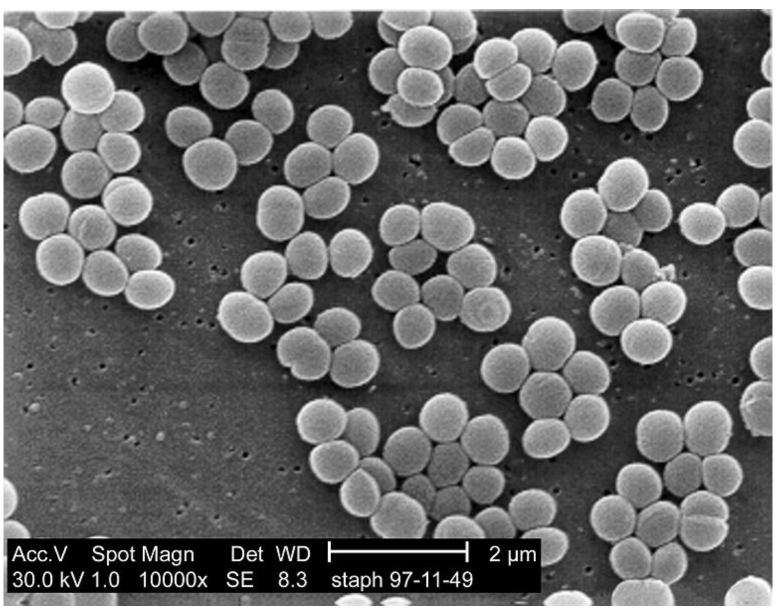

Figure 8.3: *Staphylococcus aureus* is an example of bacteria that are sphere-shaped, or cocci. (3)

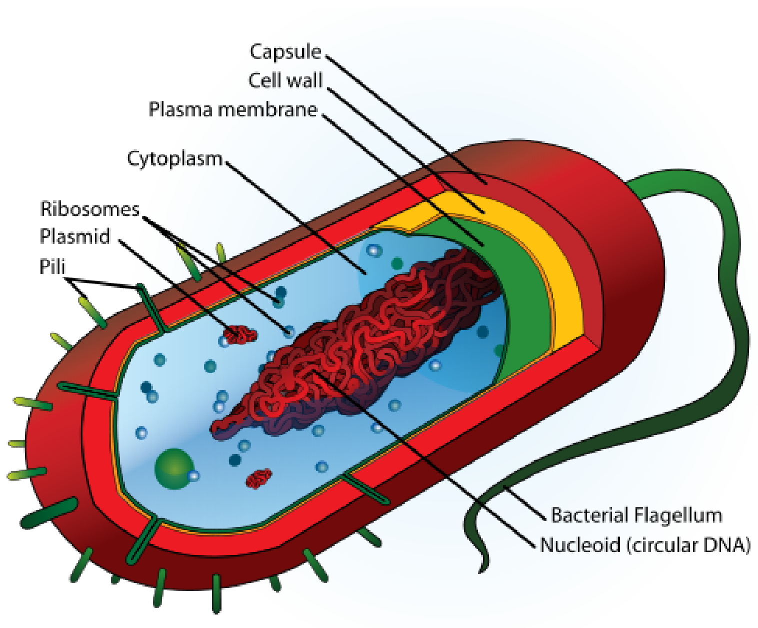

Figure 8.4: The structure of a bacterial cell is distinctive from the eukaryotic cell because of features such as an outer cell wall and the circular DNA of the nucleoid, and the lack of membrane-bound organelles. (5)

forward.

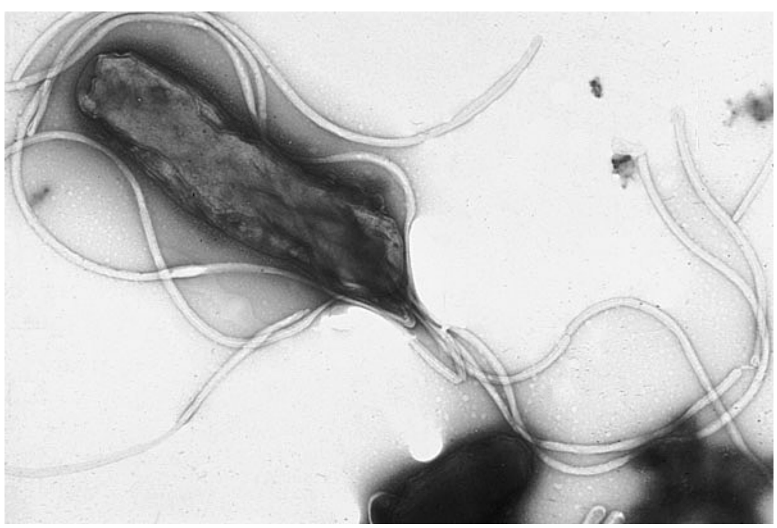

Figure 8.5: The flagella facilitate movement in bacteria. Bacteria may have one, two, or many flagella - or none at all. (6)

Obtaining Food and Energy

Bacteria obtain energy and nutrients from a variety of different methods. Bacteria known as decomposers break down wastes and dead organisms into smaller molecules to obtain nutrients and energy.

Photosynthetic bacteria use the energy of the sun, together with carbon dioxide, to make their own food (discussed in the *Cell Functions* chapter). Briefly, in the presence of sunlight, carbon dioxide and water is converted into glucose and oxygen. The glucose is then converted into usable energy. Glucose is, in essence, the "food" of the bacteria. An example of photosynthetic bacteria is **cyanobacteria,** as seen in **Figure** 8.6.

Figure 8.6: Cyanobacteria are photosynthetic bacteria. These bacteria carry out all the reactions of photosynthesis within the cell membrane and in the cytoplasm; they do not need chloroplasts. (10)

Bacteria can also be chemotrophs. **Chemotrophs** obtain energy by breaking down chemical compounds in their environment, such as nitrogen-containing ammonia. They do not use the energy from the sun. This process is important, for example, for the cycling of nitrogen through the environment. As nitrogen can not be made by living organisms, it must be continually recycled. Organisms need nitrogen to make organic compounds, such as DNA.

Some bacteria depend on other organisms for survival. For example, mutualistic bacteria live in the root nodules of legumes, such as pea plants, and make nitrogen available to the plants; in this relationship both the bacteria and the plant benefit. Other bacteria are parasitic and can cause illness. In a bacterial parasitic relationship, the bacteria benefit and the other organism is harmed. Harmful bacteria will be discussed later in the lesson.

Reproduction in Bacteria

Bacteria reproduce asexually through **binary fission.** During binary fission the chromosome copies itself (replicates), forming two genetically identical copies, then the cell enlarges and divides into two new daughter cells. The two daughter cells are identical to the parent cell (**Figure** 8.7).

Binary fission can happen very rapidly. Some species of bacteria have been shown to double their populations in less than ten minutes! (**Figure** 8.8)

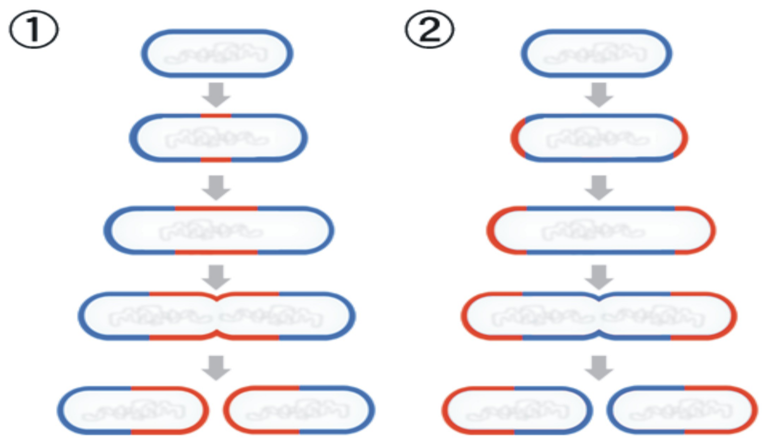

Figure 8.7: Bacteria cells reproduce by binary fission, resulting in two daughter cells identical to the parent cell. (11)

Sexual reproduction does not occur in bacteria, but genetic recombination, the combining and exchange of DNA, does happen in bacteria through three different methods: conjugation, transformation, and transduction. In **conjugation,** DNA passes through the sex pilus, a hairlike extension on the surface of many bacteria, that temporarily joins two bacteria. In **transformation,** bacteria pick up pieces of DNA from their environment. In **transduction,** bacteriophages, viruses that infect bacteria, carry DNA from one bacteria to another.

Helpful Bacteria

Bacteria are crucial in nature since they are common **decomposers,** organisms that break down dead materials and waste products. This decomposition of dead organisms is necessary so that the nutrients in their bodies can be recycled back into the environment. This recycling of nutrients, such as nitrogen, is essential for living organisms; organisms cannot produce

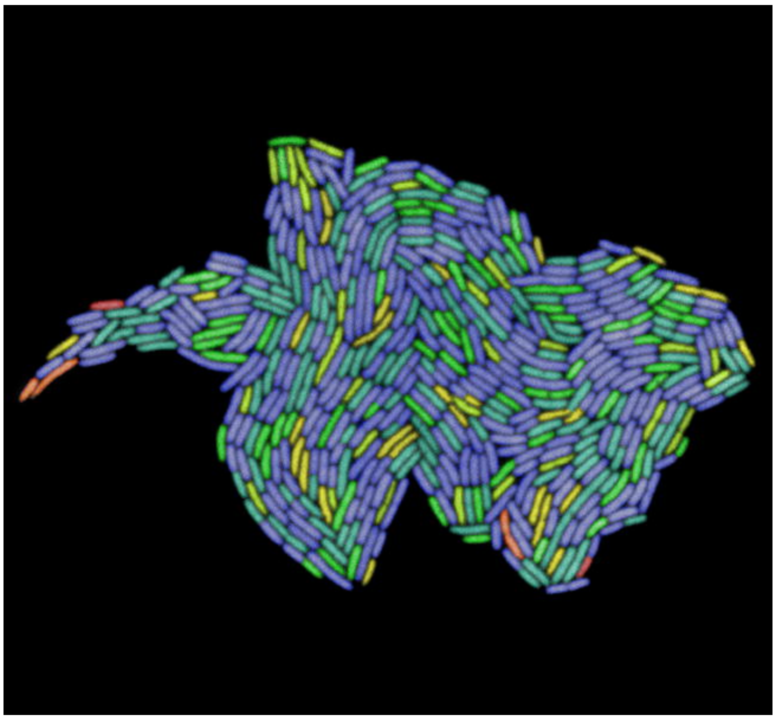

Figure 8.8: Bacteria can divide rapidly. This image is of a growing colony of *E. coli* bacteria. In the right environment the growth and division of two *E. coli* can form a colony of hundreds of bacteria in just a few hours. (12)

nutrients, so they must come from other sources. We get them from the food we eat; plants get them from the soil. How do these nutrients get into the soil? One way is from the actions of decomposers. So without decomposers, we would eventually run out of materials essential for our survival. We also depend on bacteria to decompose our wastes in sewage treatment plants.

Bacteria also help you digest your food. Several species of bacteria, such as *E. coli*, are found in large amounts in your digestive tract. In fact, bacteria cells outnumber your own cells in your gut!

Bacteria are involved in producing some foods. Yogurt is made by using bacteria to ferment milk, and cheese can also be made from milk with the help of bacteria (**Figure** 8.9). Furthermore, fermenting cabbage with bacteria produces sauerkraut.

Figure 8.9: Yogurt is made from milk fermented with bacteria. The bacteria ingest natural milk sugars and release lactic acid as a waste product, which causes proteins in the milk to form into a solid mass, which becomes the yogurt. (1)

In the laboratory, bacteria can be altered to provide us with a variety of useful materials. Bacteria can be used as tiny factories to produce desired chemicals and medicines. For example, insulin, which is necessary to treat people with diabetes, can be produced from bacteria. Through the process of transformation, the human gene for insulin is placed into bacteria. The bacteria then turn that gene into a protein. The protein can be isolated and used to treat patients. The mass production of insulin by bacteria made this medicine more affordable for patients.

Harmful Bacteria

There are also ways that bacteria can be harmful to humans and other animals. Various species of bacteria are responsible for many types of human illness, including strep throat, tuberculosis, pneumonia, leprosy, and Lyme disease. The Black Death (also known as Plague), which killed at least one third of Europe's population in the 1300's, is believed to have been caused by the bacterium *Yersinia pestis.*

Bacterial contamination can also lead to outbreaks of food poisoning. Raw eggs and undercooked meats can contain bacteria that can cause digestive tract problems. Foodborne infection can be prevented by cooking meat thoroughly and washing surfaces that have been in contact with raw meat. Washing of hands before and after handling food is also important.

Some bacteria also have the potential to be used as biological weapons by terrorists. An example is anthrax, a disease caused by the bacterium *Bacillus anthracis.* Since inhaling the spores of this bacterium can lead to a fatal infection, it is a dangerous weapon. In 2001, an act of terrorism in the United States involved *B. anthracis* spores sent in letters through the mail.

Lesson Summary

- Bacteria contain a cell wall containing peptidoglycan and a single chromosome contained in the nucleoid.
- Bacteria can obtain energy through several means including photosynthesis, decomposition, and parasitism, symbiosis, and chemosynthesis.
- Bacteria reproduce through binary fission.
- Bacteria are important decomposers in the environment and aid in digestion.
- Some bacteria can be harmful when they contribute to disease, food poisoning, or biological warfare.

Review Questions

1. What are prokaryotes?
2. What are the possible shapes that bacteria can have?
3. What is the purpose of the flagella?
4. Describe the DNA of bacteria.
5. How do bacteria reproduce?
6. How do bacteria assure genetic recombination?
7. What is a chemoautotroph?
8. How do cyanobacteria obtain energy?
9. How are bacteria important in nature?
10. How can you avoid becoming sick from the bacteria that cause food poisoning?

Further Reading / Supplemental Links

- http://www.bt.cdc.gov/agent/anthrax
- http://www.cdc.gov/ncidod/dvbid/plague/index.htm
- http://www.cdc.gov/nczved/dfbmd/disease_listing/salmonellosis_gi.html
- http://www.ucmp.berkeley.edu/bacteria/bacteria.html
- http://commtechlab.msu.edu/sites/dlc-me/zoo
- http://www.cellsalive.com/cells/bactcell.htm
- http://www.microbeworld.org/microbes/bacteria
- http://en.wikipedia.org/wiki

Vocabulary

bacilli Rod-shaped bacteria or archaea.

binary fission Type of asexual reproduction where a parent cell divides into two identical daughter cells.

cocci Sphere-shaped bacteria or archaea.

chemotrophs Organisms that obtain energy by oxidizing compounds in their environment.

conjugation The transfer of genetic material between two bacteria.

cyanobacteria Photosynthetic bacteria.

decomposers Organisms that break down wastes and dead organisms and recycle their nutrients back into the environment.

flagella Long, tail-like appendages that allow movement.

nucleoid The prokaryotic DNA consisting of a condensed single chromosome.

peptidoglycan Complex molecule consisting of sugars and amino acids that makes up the bacterial cell wall.

plasmid Ring of accessory DNA in bacteria.

prokaryotes Organisms that lack a nucleus and membrane-bound organelles; bacteria and archaea.

transduction Transfer of DNA between two bacteria with the aid of a bacteriaphage.

transformation Changing phenotypes due to the incorporation (”taking up”) of foreign DNA from the environment.

spirilli Spiral-shaped bacteria or archaea.

Points to Consider

- In the next section we will discuss the Archae. “Archae” shares the same root word as “archives” and “archaic,” so what do you think it means?
- What do you think the earliest life forms on Earth looked like?
- How do you think these early life forms obtained energy?

8.2 Lesson 8.2: Archaea

Lesson Objectives

- Identify the differences between archaea and bacteria.
- Explain how the archaea can obtain energy.
- Explain how the archaea reproduce.
- Discuss the unique habitats of the archaea.

Check Your Understanding

- What are the three shapes of bacteria?

Answer: The bacilli are rod-shaped, the cocci are sphere-shaped, and the spirilli are spiral-shaped.

- How do bacteria reproduce?

Answer: Through binary fission, producing genetically identical organisms.

- How can bacteria be harmful?

Answer: Bacteria can cause diseases such as strep throat. They can also be involved with food poisoning and biological warfare.

Introduction

For many years, archaea were classified as bacteria. However, when modern techniques allowed scientists to compare the DNA of the two prokaryotes, they found that there were two distinct types of prokaryotes, which they named archaea and bacteria. Even though the two groups might seem similar, archaea have many features that distinguish them from bacteria.

1. The cell walls of archaea are distinct from those of bacteria. In most archaea the cell wall is assembled from surface-layer proteins, providing both chemical and physical protection. The cell wall acts as a barrier, preventing macromolecules from coming into contact with the cell membrane. In contrast to bacteria, most archaea lack peptidoglycan in their cell walls.
2. The plasma membranes of the archaea also are made up of lipids that are distinct from those in other organisms.
3. Furthermore, the ribosomal proteins of the archaea resemble those of eukaryotic cells; the ribosomal proteins of archaea are different from those found in bacteria.

Although archaea and bacteria share some fundamental differences, they are still similar in many ways.

1. They both are unicellular, microscopic organisms that can come in a variety of shapes (**Figure** 8.10).
2. Both archaea and bacteria have a single circular chromosome of DNA and lack membrane-bound organelles.
3. Like bacteria, the archaea can have flagella to assist with movement.

Obtaining Food and Energy

Most archaea are chemotrophs and derive their energy and nutrients from breaking down molecules from their environment. A few species of archaea are photosynthetic and capture the energy of sunlight; chemotrophs do not capture the energy from sunlight. Unlike bacteria, which can be parasites and are known to cause a variety of diseases, there are no known archaea that act as parasites. Some archaea do live within other organisms, however, but form mutualistic relationships with their host, where both the archaea and host benefit. In other words, they actually assist the host in some way, for example by helping to digest food.

Reproduction

Like bacteria, reproduction in archaea is asexual. Archaea can reproduce through binary fission, where a parent cell divides into two genetically identical daughter cells. Archaea can

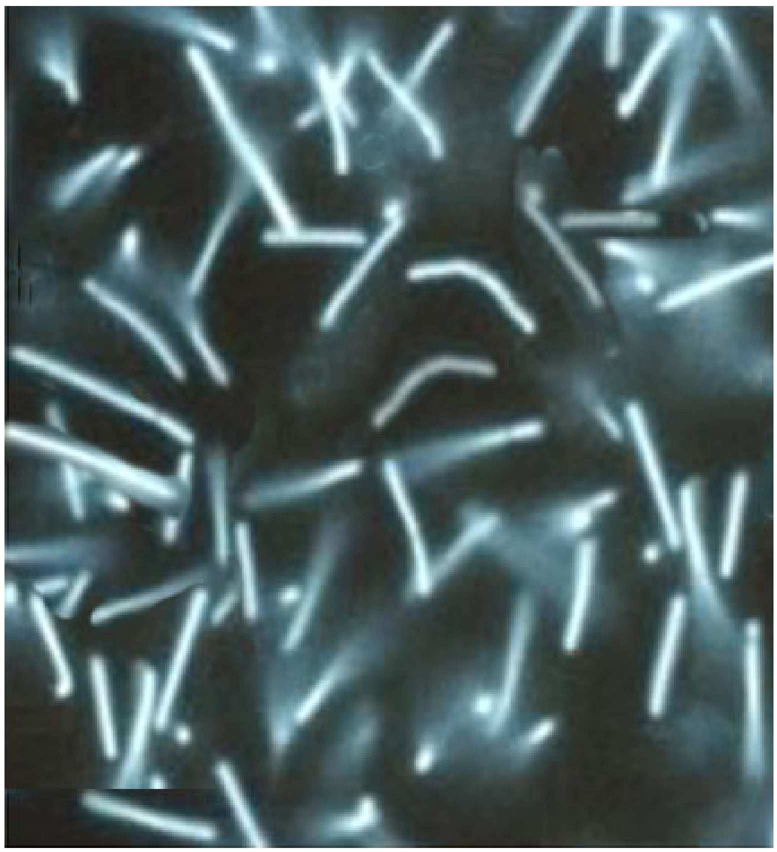

Figure 8.10: Archaea shapes can vary widely, but some are bacilli, or rod-shaped. (4)

also reproduce asexually through budding and fragmentation, where pieces of the cell break off and form a new cell, also producing genetically identical organisms.

Types of Archaea

The first archaea described were unique in that they could survive in extremely harsh environments where no other organisms could survive. For example, the **halophiles**, which means "salt-loving," live in environments with high levels of salt (**Figure** 8.11). They have been identified in the Great Salt Lake in Utah and in the Dead Sea between Israel and Jordan, which have salt concentrations several times that of the oceans.

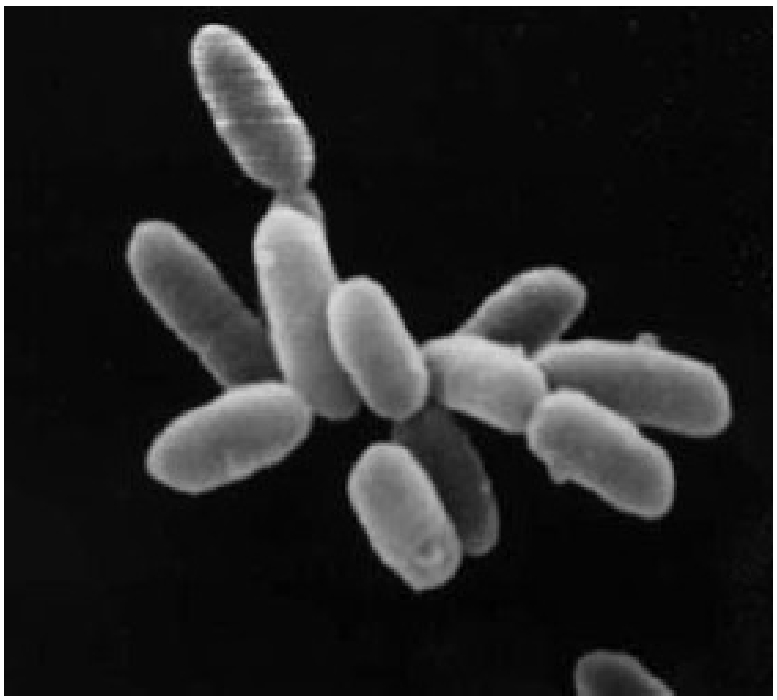

Figure 8.11: Halophiles, like the Halobacterium shown here, require high salt concentrations. (8)

The **thermophiles** live in extremely hot environments (**Figure** 8.12). For example, they can grow in hot springs, geysers, and near volcanoes. Unlike other organisms, they can thrive in temperatures near 100ºC, the boiling point of water!

Methanogens can also live in some strange places, such as swamps, and inside the guts of cows and termites. They help these animals break down cellulose, a tough carbohydrate made by plants (**Figure** 8.13). This would be an example of a mutualistic relationship. Methanogens are named for their waste product, methane, which they make as they use hydrogen gas to reduce carbon dioxide and gain energy. Methane is a greenhouse gas and

Figure 8.12: Thermophiles can thrive in hot springs and geysers, such as this one, the Excelsior Geyser in the Midway Geyser Basin of Yellowstone National Park, Wyoming. (13)

therefore contributes to global warming (see the *Environmental Problems* chapter). Therefore, the rate of methane released in swamps is of interest to scientists studying climate change.

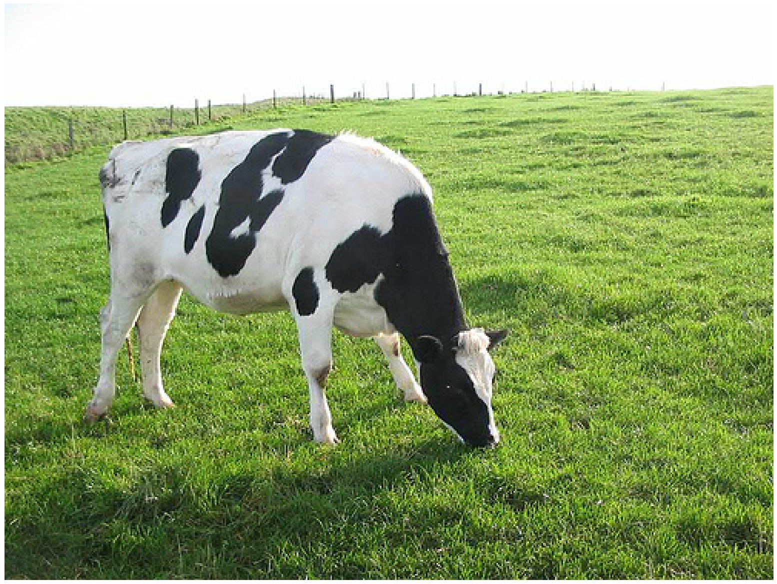

Figure 8.13: Cows are able to digest grass with the help of the methanogens in their gut. (9)

Although archaea are known for living in unusual environments, like the Dead Sea, inside hot springs, and in the guts of cows, they also live in more common environments. For example, new research shows that archaea are abundant in the soil and among the plankton in the ocean. Therefore, scientists are just beginning to discover some of the important roles that archaea have in the environment.

Lesson Summary

- Archaea are prokaryotes that differ from bacteria somewhat in their DNA and biochemistry.
- Most archaea are chemotrophs but some are photosynthetic or form mutualistic relationships.
- Archaea reproduce asexually through binary fission, fragmentation, or budding.
- Archaea are known for living in extreme environments.

Review Questions

1. What domains include the prokaryotes?
2. How are the cell walls of archaea different from those of bacteria?

3. How do archaea obtain energy?
4. How do archaea reproduce?
5. Where do halophiles live?
6. Where do thermophiles live?
7. How did methanogens get their name?
8. Name an example of a mutualistic relationship with archaea.

Further Reading / Supplemental Links

- http://www.ucmp.berkeley.edu/archaea/archaea.html
- http://www.microbeworld.org/microbes/archaea
- http://www.ncbi.nlm.nih.gov/pubmed/2112744?dopt=Abstract
- http://www.popsci.com/environment/article/2008-07/they-came-underseas
- http://www.sciencedaily.com/releases/2006/06/060605191500.htm
- http://en.wikipedia.org/wiki/Archaea

Vocabulary

archaea Single-celled, prokaryotic organisms that are distinct from bacteria.

halophiles Organisms that live and thrive in very salty environments.

methanogens Organisms that live in swamps or in the guts of cows and termites and release methane gas.

thermophiles Organisms that live in very hot environments, such as near volcanoes and in geysers.

Points to Consider

- In the next chapter we will move on to the protists and fungi. How do you think they are different from archaea and bacteria?
- Can you think of some ways that fungi can be helpful?
- Can you think of some ways that fungi can be harmful?

Image Sources

(1) Mom the Barbarian. http://www.flickr.com/photos/momthebarbarian/2441500/. CC-BY 2.0.

(2) NIAID, NIH. http://en.wikipedia.org/wiki/File:EscherichiaColi_NIAID.jpg. Public Domain.

(3) CDC. http://commons.wikimedia.org/wiki/File:Staphylococcus_aureus_01.jpg. Public Domain.

(4) http://commons.wikimedia.org/wiki/Image:Arkea.jpg. GNU-FDL.

(5) http://commons.wikimedia.org/wiki/File:Average_prokaryote_cell-_en.svg. Public Domain.

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(11) *Bacilli_division_diagram.png* . GNU-FDL.

(12) *Growing_colony_of_E._coli.jpg* . GNU-FDL.

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Chapter 9

Protists and Fungi

9.1 Lesson 9.1: Protists

Lesson Objectives

- Explain why protists cannot be classified as plants, animals, or fungi.
- List the similarities that exist between most protists.
- Identify the three subdivisions of the organisms in the kingdom Protista.

Check Your Understanding

- What are some basic differences between a eukaryotic cell and a prokaryotic cell?
- List some characteristics that all cells have.

Introduction

So what's a protist? Is it an animal or plant? **Protists** are organisms that belong to the kingdom Protista. These organisms, all **eukaryotes** and mostly **unicellular,** do not fit neatly into any of the other kingdoms. You can think about protists as all eukaryotic organisms that are neither animals, nor plants, nor fungi. Even among themselves, they have very little in common – very simple structural organization and a lack of specialized structures are all that unify them as a group. Although the term *protista* was coined by Ernst Haeckel in 1866, the kingdom Protista was not an accepted classification in the scientific world until the 1960s.

What are Protists?

These unique and varied organisms demonstrate such unbelievable differences that they are sometimes called the "junk drawer kingdom". This kingdom contains the eukaryotes that cannot be classified into any other kingdom. Most protists, such as the ones shown in (**Figure** 9.1), are so tiny that they can be seen only with a microscope. Protists are mostly unicellular eukaryotes that exist as independent cells.However, a few protists are multicellular and surprisingly large.The protists that do form colonies (are multicellular) do not, however, show cellular specialization or differentiation into tissues. Cellular specialization is a major feature of multicellular organisms absent in these protists. For example, kelp is a multicellular protist and is over 100-meters long.

A few characteristics unify the protists:

1. they are eukaryotic which means they have a nucleus
2. most have mitochondria
3. many are parasites
4. they all prefer aquatic or at least moist environments.

For classification, the protists are divided into three groups: animal-like protists, plant-like protists, and fungi-like protists. But remember they are not animals or plants or fungi, they are protists ((**Figure** 9.2)). As there are many different types of protists, the classification of protists can be difficult. Recently, molecular analysis has been used to confirm evolutionary relationships among protists. These molecular studies compare DNA sequences. Protists with higher amounts of common DNA sequences are evolutionarily closer related to each other. Protists are widely used in industry and in medicine.

Protists Obtain Food

Protists need to perform the necessary cellular functions to stay alive. These include the need to grow and reproduce, the need to maintain homeostasis, and the need for energy. So they need to obtain food to provide the energy to enable these functions.

So how are animal-like, plant-like, and fungi-like protists distinguished from each other? Mainly through how they get their carbon. Of course, carbon is essential in the formation of organic compounds: carbohydrates, lipids, proteins, and nucleic acids. You get it from eating, as do other animals.

For such simple organisms, protists get their food in a complicated process. Although there are many photosynthetic protists (such as the algae discussed in the Plant-like Protists section below) that get their energy from sunlight, many others still must swallow their food through a process like endocytosis. Endocytosis was discussed in the *Cell Functions* chapter.

Figure 9.1: Protists come in many different shapes. (11)

Figure 9.2: This slime mold is a protist. Slime molds had previously been classified as fungi but are now placed in the kingdom Protista. Slime molds live on decaying plant life and in the soil. (7)

When a protist is ready to eat, it will wrap its cell wall and cell membrane around its prey, which is usually bacteria. In doing so, it creates a food vacuole or a sort of "food storage compartment." Next the protist produces toxins which paralyze its prospective dinner. Once paralyzed, the food material simply moves by force of gravity through the vacuole and into the cytoplasm of the hungry protist. Other protists are parasitic, and absorb nutrients meant for their host, harming the host in the process.

Animal-like Protists

Animal-like protists are called protozoa. **Protozoa** are unicellular eukaryotes that share certain traits with organisms in the animal kingdom. Those traits are mobility and heterotrophy. Animal-like protists are **heterotrophs** which mean they get their carbon from outside sources—in other words, they eat organic materials. Animal-like protists are very tiny measuring only about 0.01–0.5mm. Animal like protists include the zooflagellates, ciliates, and the sporozoans (**Figure** 9.3).

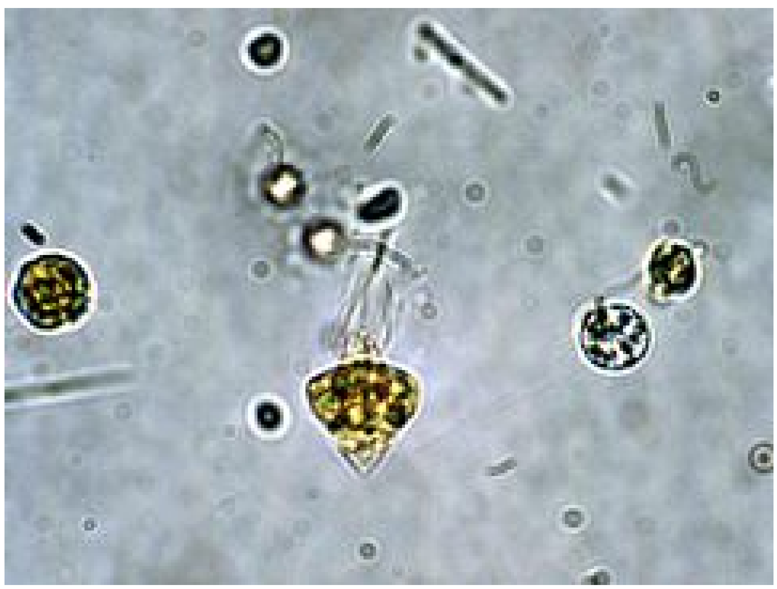

Figure 9.3: Euglena are animal-like protists. Over 1000 species of Euglena exist and are used in industry in the treatment of sewage. (5)

Although most protists obtain nutrition through pinocytosis, some protists literally "eat with their tails". The tail of a protist is a flagellum and these protists are called **flagellates**. Flagellates acquire oxygen and nitrogen by constantly whipping the flagellum back and forth in a process of filter-feeding. The whipping of the flagellum creates a current that brings food into the protist.

A **flagellum** (plural: **flagella**), is a tail-like structure that projects from the cell body of certain prokaryotic and eukaryotic cells, and it usually functions in helping the cell move.

A flagellum is a cellular structure and not an organelle. Prokaryotic cells may also have flagella.

Different Kinds of Animal-like Protists

Are there different types of animal-like protists? How are they distinguished? You can distinguish one from the other based on how they get around or rather, by their method of locomotion. For example, flagellates have long flagella or tails. Flagella rotate in a propeller-like fashion. An example of a flagellate is the *Trypanosoma*, which causes African sleeping sickness. Other protists have what is called a "transient pseudopodia" or a moving fake foot. Here's how it works. The cell surface extends out a membrane and the force of this membrane propels the cell forward. An example of a protist with a pseudopod is the amoeba. Another way to move if you are a protist is by the movement of cilia. The paramecium has cilia that propel it. Cilia are thin, tail-like projections that extend about 5–10 micrometers outwards from the cell body. Cilia beat back and forth, propelling the protist along. A few protists are non-mobile such as the toxoplasma. Protists such as the toxoplasma form **spores** and are known as sporozoans; these protists but do not have any mobility themselves.

Plant-like Protists

Plant-like protists are **autotrophs.** This means that they produce complex organic compounds from simple inorganic molecules using a source of energy such as sunlight. Plant-like protists live in soil, in seawater, on the outer covering of plants, in ponds and lakes (**Figure** 9.4). Protists like these can be unicellular, or multicellular. Some protists, such as kelp live in huge colonies in the ocean. Plant-like protists are essential to the environment; they produce oxygen (a product of photosynthesis) which sustains other organisms and they play an essential role in aquatic food chains. Plant-like protists are classified into a number of basic groups (**Table** (9.1)).

Table 9.1: **Plant-like Protists**

Phylum	Description	Number (approximate)	Example
Chlorophyta	green algae - related to higher plants	7,500	*Chlamydomnas, Ulva, Volvox*
Rhodophyta	red algae	5,000	*Porphyra*
Phaeophyta	brown algae	1,500	*Macrocystis*
Chrysophyta	diatoms, golden-brown algae, yellow-green algae	12,000	*Cyclotella*
Pyrrophyta	dinoflagellates	4,000	*Gonyaulax*

Table 9.1: (continued)

Phylum	Description	Number (approximate)	Example
Euglenophyta	euglenoids	1,000	*Euglena*

Figure 9.4: Red algae are a very large group of protists making up about 5,000–6,000 species. They are mostly multicellular, live in the ocean. Many red algae are seaweeds and help create coral reefs. (1)

Fungus-like Protists

Fungus-like protists are heterotrophs that have cell walls and reproduce by forming spores. Fungus-like protists mostly immobile but some develop movement at some point in their lives. There are essentially three types of fungus-like protists: water molds, downy mildews, and slime molds (**Table** (9.2)). Slime molds represent the characteristics of the fungus-like protists. Most slime mold measure about one or two centimeters, but a few slime molds are as big as several meters. They are often bright colors such as a vibrant yellow. Others are brown or white. Stemonitis is a kind of slime mold which forms small brown bunches on the outside of rotting logs. Physarum polycephalum lives inside rotting logs and is a gooey mesh of yellow "threads" that are a several centimeters long. Fuligo, sometimes called "vomit mold," is a yellow slime mold found in decaying wood.

Table 9.2: **Fungus-like Protists**

Protist	Source of Carbon	Environment	Characteristics
omycetes: water molds (**Figure** 9.6)	decompose remains, parasites of plants and animals	most live in water	Causes a range of diseases in plants; common problem in greenhouses where the organism kills newly emerged seedlings; have been employed as biocontrol agents; includes the downy mildews, which are easily identifiable by the appearance of white "mildew" on leaf surfaces.
Mycetozoa: slime molds (**Figure** 9.5)	dispose of dead plant material, feed on bacteria	common in soil, on lawns, and in the forest commonly on deciduous logs	Includes the cellular slime mold, which involves numerous individual cells attached to each other, forming one large "supercell," essentially a bag of cytoplasm containing thousands of individual nuclei. The plasmodial slime molds spend most of their lives as individual unicellular protists, but when a chemical signal is secreted, they assemble into a cluster that acts as one organism.

Figure 9.5: An example of a slime mold. (6)

Figure 9.6: An aquatic insect nymph attacked by water mold. (2)

Importance of Protists

Earth would be uninhabitable if it were not for the 80 different groups of organisms called protists. Protists produce almost one-half of the oxygen on the planet, decompose and recycle nutrients that humans need to live, and make up a huge portion of the food chain. Many protists are commonly used in medical research. For example, medicines made from protists are used in treatment of high blood pressure, digestion problems, ulcers, and arthritis. Other protists are used in molecular biology and genetics studies. Slime molds are used to analyze the chemical signals used in directing cellular activities. Protists are also valuable in industry. Carrageenan, extracted from red algae, is used as a gel to solidify puddings, ice cream, and candy. Chemicals from other kinds of algae are used in the production of many kinds of plastics.

Lesson Summary

- Protists are highly diverse organisms that belong to the kingdom Protista.
- Protists are divided into three subgroups: animal-like protists, plant-like protists, fungus-like protists.
- Animal-like protists are unicellular eukaryotes that that share certain traits with organisms in the animal kingdom such as mobility and heterotrophy.
- Plant-like protists are unicellular or multicellular autotrophs that live in soil, in seawater, on the outer covering of plants, in ponds and lakes.
- Fungus-like protists, such as water molds, downy mildews, and slime molds, are heterotrophs that reproduce by forming spores.

Review Questions

1. List the unifying characteristics of protists?
2. List two ways that protists obtain food.
3. Describe the characteristics of an animal-like protist.
4. Describe the characteristics of a plant-like protist.
5. Describe the characteristics of a fungi-like protist.
6. Name three kinds of fungi-like protists.
7. Write a convincing essay demonstrating the importance of protists to life on Earth.
8. Imagine that you are a scientist delivering a paper called "Protists: the Junk-Drawer Kingdom" What would you say in your paper to explain your choice of title?

Further Reading / Supplemental Links

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Vocabulary

autotroph Organism that produces complex organic compounds from simple inorganic molecules using a source of energy such as sunlight.

cilia Thin, tail-like projections that extend about 5–10 micrometers outwards from the cell body; beat back and forth, propelling the protist along.

filter-feeding Characteristic of flagellates; acquire oxygen and nitrogen by constantly whipping the flagellum back and forth; creates a current that brings food into the protist.

flagellum A tail-like structure that projects from the cell body of certain prokaryotic and eukaryotic cells, and it usually functions in helping the cell move.

heterotroph Organism which obtains carbon from outside sources.

protist Eukaryotic organism that belongs to the kingdom Protista; not a plant, animal or fungi.

protozoa Animal-like protists

transient pseudopodia A moving fake foot; the cell surface extends out a membrane and the force of this membrane propels the cell forward.

Points to Consider

- Fungi comprise one of the eukaryotic kingdoms. Think about what might distinguish a fungi-like protist from a true fungus?
- Given the vast differences between the protists discussed in this lesson, think about the possibilities of dividing this kingdom into additional kingdoms. How might that division be accomplished? Is that a good idea or would it just lead to confusion?

9.2 Lesson 9.2: Fungi

Lesson Objectives

- Describe the characteristics of fungi.
- Identify structures that distinguish fungi from plants and animals.
- Explain how fungi can be used in industry.

Check Your Understanding

- What is a significant difference between a protist and other eukaryotic organisms?
- What are some of the distinguishing characteristics of fungus-like protists?

Introduction

Ever notice blue-green mold growing on a loaf of bread? Do you like your pizza with mushrooms? Has a physician ever prescribed an antibiotic for you? If so, then you have encountered fungi. Fungi are organisms that belong to the kingdom Fungi (**Figure** 9.7). Our **ecosystem** needs fungi. Fungi help decompose matter and make nutritious food for other organisms. Fungi are all around us and are useful in many ways to the natural world and to humans in industry.

What are Fungi?

If you had to guess, would you say fungus is a plant or animal? Scientists used to debate about which kingdom to place fungi in. Finally they decided that fungi were plants. But they were wrong. Now scientists know that fungi are not plants at all. Fungi are very different from plants. Fungi belong to their own kingdom called the kingdom Fungi.

Plants are autotrophs, meaning that they make their own "food" using the energy from sunlight. Fungi are heterotrophs, which means that they obtain their "food" from outside

Figure 9.7: These many different kinds of organisms demonstrate the huge diversity within the kingdom Fungi. (4)

of themselves. In other words, they must "eat" or ingest their food like animals or many bacteria do.

Yeasts, molds, and mushrooms are all different kinds of fungi (**Figure** 9.8). There may be as many as 1.5 million species of fungi. You can easily see bread mold and mushrooms without a microscope, but most fungi you cannot see. Fungi is either too small to be seen without a microscope or it lives where you cannot see it easily such as deep in the soil, or under decaying logs, or inside plants or animals. Some fungi even live in or on top of other fungi.

Figure 9.8: The blue in this blue cheese is actually mold. (12)

Fungi and Symbiotic Relationships

If it were not for fungi, many plants would go hungry. In the soil fungi grow closely around the roots of plants. Then as they form that close relationship, the plant and the fungus "feed" one another. The plant provides glucose and sucrose to the fungus that the plant makes through photosynthesis which the fungus cannot do. The fungi then provides minerals and water to the roots of the plant. This form of helping each other out is called **mycorrhizal symbiosis.** Mycorrhizal means "roots" and symbiosis means "relationship" between organisms (**Figure** 9.9).

Figure 9.9: This mushroom and tree live in symbiosis with each other. (3)

Lichens

Have you ever seen an organism called a **lichen?** Lichens are crusty, hard growths that you might find on trees, logs, walls, and rocks. Although lichens may not be the prettiest organisms in nature, they are unique. A lichen is really two organisms that live very closely together—a fungus and a bacteria or algae. The cells from the algae or bacteria live inside the fungi. Each organism provides nutrients for the other. Consequently, a lichen is the result of the symbiosis between a fungus and an another organism.

The earliest scientist to study lichens was Beatrix Potter. You might have heard of her as the author and illustrator of the Peter Rabbit stories. Before Beatrix Potter became a famous author, she was a botanist and studied hundreds of different kinds of fungi. She was the first person to explain the symbiotic relationship between bacteria and fungi. She even presented a scientific paper to the British scientific community in 1897.

Fungi and Insects

Many insects have a symbiotic relationship with certain types of fungi. For example, ants and termites grow fungi in underground "fungus gardens" that they create. Then when the ants or termites have eaten a big meal of wood or leaves, they eat some fungus from their gardens. The fungus helps them digest the **cellulose** in the wood or leaves. The two species are actually dependent on each other for survival. Ambrosia beetles live in the bark of trees. Like ants and termites, they grow fungi inside the bark of trees where they live and use it to help digest their food.

Fungi as Parasites

Although lots of symbiotic relationships help both organisms, sometimes one of the organisms is harmed. When that happens, the organism that benefits and is not harmed is called a parasite. Have you ever heard of Dutch elm disease? In the late 1960s elm trees in the United States began to die. Since then much of the species has been eliminated. The disease was caused by a fungus that acted as a parasite. The fungus that killed the trees was carried by beetles that inoculated the tree with the fungus. The tree tried to stop the growth of the fungus by blocking its own ability to gain water. However, without water the tree soon dies.

Some parasitic fungi cause human diseases such as athlete's foot and ringworm. These fungi feed on the outer layer of warm, moist skin.

Fungi as Predators

It might seem that fungi growing on a tree trunk or a mushroom in your yard are passive and participating in very little activity, but did you know that some fungi are actually hunters? Some fungi trap nematodes. A nematode is a kind of a worm and is often dinner to fungi. These hungry fungi live deep in the soil where they set traps for unsuspecting nematodes by making a circle with their **hyphae.** Hyphae are sort of the "arms and legs" of a fungus; they look like cobwebs and can be sticky. Fungi set out circular rings of hyphae with a lure inside which brings the nematode inside the fungus (**Figure** 9.10).

Fungi are Good Eaters

Fungi can grow fast because they are such good eaters. Fungi have lots of surface area and this large surface area "eats." Surface area is how much exposed area an organism has compared to their overall volume, and in the mushroom for example, most of that surface area is actually underground. They also have special enzymes that they can squirt into their environment which helps them digest large organic molecules. Sort of like how you might cut up your meat or vegetables before eating, fungi "cut up" large molecules such as sugars, proteins, and lipids into smaller molecules. Then the fungi absorb the nutrients into their cells.

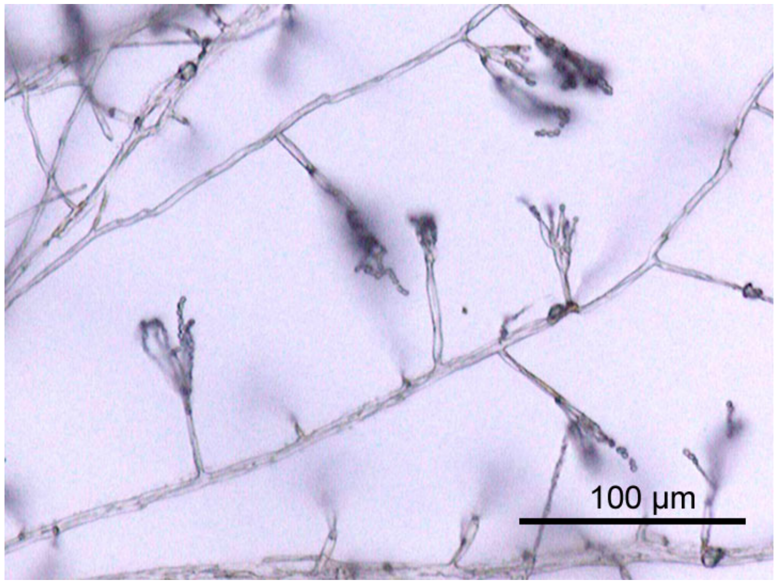

Figure 9.10: Hyphae are the cobwebby arms and legs of fungi. (9)

Fungi Body Parts

Fungi have a cell wall, hyphae, and specialized structures for reproduction. The hyphae are thread-like structures which interconnect and bunch up into **mycelium.** Ever see mold on a damp wall or on old bread? The thing that you are seeing is really mycelia. The hyphae and mycelium help the fungi absorb nutrients from living hosts. Other specialized structures are used in sexual reproduction. One example is a fruiting body. A mushroom is a **fruiting body**, which is the part of the fungus that produces the spores. Spores are the basic reproductive units of fungi.

Fungi Reproduction

Reproduction of fungi is different for different fungi. Many fungi reproduce both sexually or asexually, while some reproduce only sexually and some only asexually. **Asexual reproduction** takes only one parent and **sexual reproduction** takes two parents.

Asexual Reproduction

Fungi reproduce asexually through three methods: spores, budding, and mycelial fragmentation. Asexual spores are formed by the fungi and released to create new fungi. Have you ever seen a puffball? A puffball is a kind of fungus that has thousands of spores in a giant ball. Eventually the puffball bursts and releases the spores in a huge "puff". In budding, the fungus grows part of its body which eventually breaks off. The broken-off piece becomes a "new" organism. Many fungi can reproduce by mycelial fragmentation or splitting off of the mycelia. A fragmented piece of mycelia can eventually produce a new colony of fungi.

Asexual reproduction is faster and produces more fungi than sexual reproduction. For some species of fungi, asexual reproduction is the only way possible to reproduce. Asexual reproduction is controlled by many different factors, including environmental conditions such as the amount of sunlight and CO_2 the fungus receives, as well as the availability of food.

Sexual Reproduction

Almost all fungi can reproduce with **meiosis.** Meiosis is a type of cell division where haploid cells are produced (discussed in chapter titled *Cell Division, Reproduction and DNA*). But meiosis in fungi is really different from sexual reproduction in plants or animals.

Meiosis occurs in **diploid** cells and is a process that produces **haploid** cells. A diploid cell is a cell with two sets of chromosomes–one from each parent. A haploid cell has one set of chromosomes. In meiosis, the chromosomes duplicate once, and then after two more divisions, four haploid cells are produced. Each haploid cell has half the chromosome number of the parent cell. However, in fungi, meiosis occurs right after two haploid cells fuse, producing four haploid cells. Mitosis then produces a haploid multicellular "adult" organism or haploid unicellular organisms. Mitosis is cell division that results in two genetically identical offspring cells.

Other Sexual Processes

Some species of fungi exchange genetic material by **parasexual** processes. This means that some haploid nuclei in the fungi cells may fuse and form diploid nuclei. These nuclei rarely exist and are usually very unstable. Chromosomes are lost during later mitotic divisions which sometimes makes the offspring fungus genetically different from the parents.

Classification of Fungi

Scientists used to think that fungi were members of the Plant kingdom. They thought this because fungi had several similarities to plants. For example, fungi and plants are usually **sessile** with a leaf or flower that is attached to a stem. Also:

- Both fungi and plants have similar **morphology** or structure.
- Plants and fungi live in the same kinds of habitats, such as growing in soil.
- Plants and fungi both possess a cell wall; animals cells do not have a cell wall.

But scientists now know that fungi are their own separate kingdom — the kingdom Fungi. And that they separated nearly one billion years ago.

Physiological and Morphological Traits

There are a number of characteristics that distinguish fungi from other eukaryotic organisms.

1. Fungi cannot make their own food like plants can since they do not have any of the right equipment for photosynthesis. Fungi are more like animals and some bacteria in that they have to obtain their food from outside sources.
2. The cell walls in lots of species of fungi is **chitin.** Chitin is a nitrogen-containing material that you find in the shells of animals such as beetles and lobsters. But the cell wall of a plant is not made of chitin but rather a carbohydrate called cellulose.
3. Unlike many plants, most fungi do not have a good vascular system. A vascular system is the way that an organism transports fluids such as water and nutrients. In all plant the vascular system is made up of structures called xylem and phloem. But fungi do not have xylem or phloem. This lack of vascular structures distinguishes fungi from plants.
4. However, one characteristic is entirely unique to fungi and does not exist at all in animals or plants. That characteristic is hyphae which combine in groups called mycelium, as described above.

The Evolution of Fungi

Fungi appeared during the Paleozoic Era, a geologic time period lasting from about 570 million to 248 million years ago, and the time when fish, insects, amphibians, reptiles, and land plants appeared. The first fungi were most likely aquatic, and had flagellum that released spores. The first land fungi probably appeared in the Silurian period (443 million years ago to about 416 million years ago), a geologic period during which land plants also appeared.

Roles of Fungi

Fungi are found all over the globe in many different kinds of habitats. Fungi even thrive in deserts. Most fungi however are found on land rather than in the ocean, but some species live only in marine habitats. Fungi are extremely important to these ecosystems because they are one of the major decomposers of organic material in most terrestrial ecosystems. Scientists have estimated that there are nearly 1.5 million species of fungi.

Importance of Fungi for Human Use

Humans use fungi for food preparation or preservation and other purposes. For example, yeasts are required for fermentation of beer, wine and bread (**Figure** 9.11). Some fungi are used in the production of soy sauce and tempeh, a stable source of protein, like tofu, found in South East Asia. Mushrooms are used in the diet of people all over the globe. Other fungi are producers of antibiotics, such as penicillin. The chitin in the cell walls of fungi, have wound healing properties.

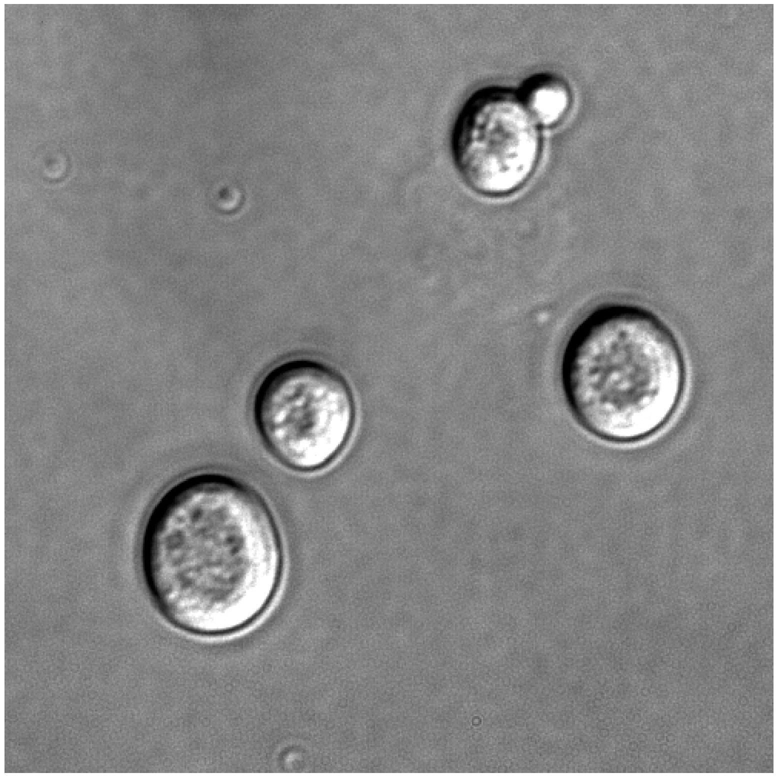

Figure 9.11: Baker's yeast or *Saccharomyces cerevisiae*, a single-cell fungus, is used in the baking of bread and in making wine and beer through fermentation. (8)

Edible and Poisonous Fungi

Some of the best known types of fungi are mushrooms–both edible and poisonous (**Figure** 9.12). Many species are grown commercially, but others must be harvested from the wild. When you order a pizza with mushrooms or add them to your salad, you are most likely eating *Agaricus bisporus*, the most commonly eaten species. Other mushroom species are gathered from the wild for people to eat or for commercial sale.

Have you ever eaten blue cheese? Do you know what makes it blue? You guessed it. Fungus. For certain types of cheeses, producers inoculate milk curds with fungal spores to promote the growth of mold which makes the cheese blue. Molds used in cheese production are safe for humans to eat.

Many mushroom species are poisonous to humans—some mushrooms will simply give you a stomach ache while others may kill you. Some mushrooms you can eat when they are cooked but are poisonous when raw.

Figure 9.12: Some of the best known types of fungi are the edible and the poisonous mushrooms. (10)

Fungi in the Biological Control of Pests

Some fungi work as natural pesticides. For example in agriculture, some fungi may be used to limit or kill harmful organisms like mites, pest insects, certain weeds, worms, and other fungi that harm or even kill crops.

Lesson Summary

- Fungi are in their own kingdom based on their structures, ways of obtaining food, and on their means of reproduction.
- Fungi live with other organisms in symbiotic relationships.
- Fungi reproduce asexually, sexually and parasexually.
- Fungi appeared during the Paleozoic Era.
- Fungi are widely used in industry and medicine.

Review Questions

1. What two characteristics distinguishes fungi from plants?
2. How many species of fungi exist?
3. Define mycorrhizal symbiosis.
4. Describe the symbiotic relationship of a lichen.
5. How was Beatrix Potter important to the scientific world?
6. Describe the relationship between the ambrosia beetle and fungi?

7. Name two human diseases caused by fungus.
8. When you see mold what body part of the fungus are you observing?
9. Describe asexual reproduction in fungi.
10. Describe sexual reproduction in fungi.

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Vocabulary

asexual reproduction Reproduction involving only one parent; fungi reproduce asexually through three methods: spores, budding, and mycelial fragmentation.

budding Asexual reproduction in which the fungus grows part of its body which eventually breaks off; the broken-off piece becomes a new organism.

chitin A nitrogen-containing material found in the cell wall of fungi; also found in the shells of animals such as beetles and lobsters.

fruiting body Specialized structure used in sexual reproduction; part of the fungus that produces the spores.

heterotroph Organism which obtains carbon ("food") from outside of themselves.

hyphae Thread-like structures which interconnect and bunch up into mycelium; helps bring food, such as a worm, inside the fungus; : the "arms and legs" of a fungus.

lichen A symbiotic relationship between a fungus and a bacteria or algae; each organism provides nutrients for the other.

meiosis A type of cell division where haploid (one set of chromosomes) cells are produced.

mycelial fragmentation Asexual reproduction involving splitting off of the mycelia; a fragmented piece of mycelia can eventually produce a new colony of fungi.

mycelium Help the fungi absorb nutrients from living hosts; composed of hyphae.

mycorrhizal symbiosis A relationship between fungi and the roots of plants where both benefit; the plant provides glucose and sucrose to the fungus that the plant makes through photosynthesis; the fungi provides minerals and water to the roots of the plant.

parasite The organism that benefits in a relationship between two organisms in which one is harmed.

spores The basic reproductive units of fungi.

Points to Consider

- Plants are fascinating organisms and are widely diverse. Although scientists used to think that fungi were plants, we now know that plants are fungi are separate. In this lesson we have discussed fungi. Now think about what sets plants apart from fungi?

Image Sources

(1) http://en.wikipedia.org/wiki/File:Laurencia.jpg. GNU-FD.

(2) *An aquatic insect nymph attacked by water mold.*. GNU-FDL.

(3) http://en.wikipedia.org/wiki/File:Oudemansiella_nocturnum.JPG. Public Domain.

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(5) EPA. http://en.wikipedia.org/wiki/File:Euglena_EPA.jpg. Public Domain.

(6) *An example of a slime mold.*. Public Domain.

(7) http://en.wikipedia.org/wiki/Image:Slime_mold.jpg. GNU-FDL.

(8) http://en.wikipedia.org/wiki/Image:S_cerevisiae_under_DIC_microscopy.jpg. GNU-FDL.

(9) http://en.wikipedia.org/wiki/File:Penicillium.jpg. GNU-FDL.

(10) http://en.wikipedia.org/wiki/Image:Asian_mushrooms.jpg. CC-BY-SA 2.0.

(11) *Protists come in many different shapes.*. GNU-FDL.

(12) *The blue in this blue cheese is actually mold.*. GNU-FDL.