LIFE SCIENCE

GRADE LEVEL: 6-8TH GRADE

YEARLONG COURSE

NOVARE

Life Science supports our signature philosophy of science education based on wonder, integration, and mastery. We always seek to build on and stimulate the student's innate sense of wonder at the marvels found in nature. Integration refers to the **epistemology**, **mathematics**, and **history** embedded in the text, and a curriculum designed to help develop the student's facility with using **language** to communicate scientific concepts. *Life Science* is designed to be used in a mastery-learning environment, using the mastery teaching model John developed and describes in *From Wonder to Mastery: A Transformative Model for Science Education*. When teachers use this mastery-learning model, the result is high student achievement and exceptional long-term retention for all students.

SUPPORT RESOURCES

Two major support resources are available to accompany *Life Science*. They include:

The Apprentice's Companion for Life Science

Our *Apprentice's Companion* series represents a completely new approach for laboratory curriculum. This volume is much more than a lab manual—it is a combination lab manual, sketch book, commonplace book, and lab journal. Sprinkled throughout *The Apprentice's Companion* are historical notes, poems, artwork, and quotes, all designed to make each experiment a rich, multi-disciplinary activity. For maximum classroom flexibility, the twenty-six experiments comprise a blend of short (10–15 minute) and longer (full-period) activities.

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The following materials are accessible exclusively through Novare Science:

- a full year of weekly, cumulative quizzes
- two semester exams
- a document containing all keys and sample answers to all verbal questions (text and exams)
- a full year of Weekly Review Guides
- a document with recommendations for teaching the course
- a lesson list and example calendar

ABOUT NOVARE SCIENCE

Novare Science is an imprint of Classical Academic Press that focuses on the highest-quality science curriculum for Christian schools and home schools. Founded by educator John D. Mays, Novare Science offers a completely unique approach to secondary science curriculum. For more information on our vision for secondary science education, please refer to the Overview section on pg. 3-7 in this series of samples.

CONTACT US

Our team is here to assist as you choose curricula that will be the best fit for your classroom. We encourage you to take advantage of the following resources:

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SAMPLE CHAPTERS

The following pages contain samples from the text. The Table of Contents is shown, as well as Chapters 1 and 2.

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Contents

Chapter 1 What Is Life Science?

Science, Life Science, and Scientific Knowledge

Though unfamiliar to most people, the takin is the national mammal of Bhutan. It lives in the mountains of Asia. In China, it shares its range with the giant panda. The takin is very large for a mountain mammal, weighing up to 770 pounds, about the size of a small American bison. Closely related to wild sheep, this hoofed mammal has no trouble climbing up and down steep mountain slopes. The takin's large snout holds equally large sinus cavities that warm the cold mountain air before it reaches the animal's lungs. Its skin produces an oil that protects the animal from rain and fog. Takins eat many kinds of plants, including some that are poisonous to most grazing animals. They search out salt licks for mineral nutrients. Takins gather in large herds of 50 or more in the spring.

You can probably name several other mammals that share some of the characteristics of the takin. You might think of antelopes, oxen, sheep, goats, and maybe even the barnyard cow. Grouping animals into families is a scientific task known as taxonomy: naming living organisms and placing them into groups with shared features. Swedish botanist Carl Linnaeus developed an early system of taxonomy that continues to develop with new scientific fields of study.

OBJECTIVES

After studying this chapter and completing the exercises, you should be able to do each of the following tasks, using supporting terms and principles as necessary.

1. List and briefly describe the series of characteristics scientists use to identify life.
2. Define science, theory, hypothesis, and scientific fact.
3. Describe the Cycle of Scientific Enterprise by describing each major step in the cycle and explaining its relationships to other steps.
4. Distinguish between theories and hypotheses and give actual examples of each.
5. Distinguish between scientific facts, theories, and truth.
6. Define truth and give examples of true statements.
7. Explain why science can be described as "mental model building."
8. Describe the three ways we know truth.
9. Explain why scientific facts and theories are regarded as provisional.
10. Briefly describe the contributions of Anton van Leeuwenhoek, Robert Hooke, Matthias Jakob Schleiden, and Theodor Schwann to the cell theory.
11. State the key ideas in the cell theory.
12. Describe the importance of Francesco Redi's and Louis Pasteur's experiments.

VOCABULARY TERMS

You should be able to define or describe each of these terms in a complete sentence or paragraph.

1. Cycle of Scientific Enterprise
2. experiment
3. General Revelation
4. hypothesis
5. mental model
6. science
7. scientific fact
8. Special Revelation
9. theory
10. truth

1.1 The Characteristics of Living Things

1.1.1 Life Is a Process

In many ways, the study of living things is the most exciting adventure there is in all of science. This is because living things are still mysterious and full of wonder for us, despite thousands of years of study!

What is life? Although distinguishing between living and nonliving things would seem like a simple task, scientists find it difficult to define *life* because life is not a thing, but a process, or perhaps we should say that life involves complex systems of connected processes. But despite our difficulty in defining life, we know where it comes from. David reminds us in Psalm 33:6 that life has its origins in the breath of God: "By the word of the Lord the heavens were made, and by the breath of his mouth all their host." His poetic description separates the creation into two large categories: nonliving (things made by the word of the Lord) and living (creatures given life by the breath of God).

Instead of depending on a definition to identify life, scientists describe life in terms of a cluster of six characteristics found in all living things: living things are organized; gather matter and energy; grow, develop, and reproduce; use and pass on genetic information; respond to stimuli; and adapt to their environment. This is a lengthy list that contains within it much of the study of life science. We'll look at each item briefly here and more thoroughly in the chapters that follow.

1.1.2 Living Things are Organized

Your body and the tree in your backyard are both highly organized, as suggested by Figure 1.1. Within your body and within the tree, atoms—the smallest units of elements—join to form organic molecules such as carbohydrates, proteins, nucleic acids, and lipids. These molecules come together in cells, the smallest units of life. Some living things, such as bacteria, are single-celled. But both your body and the tree are multicellular organisms. The cells in your body and in the tree specialize to perform certain functions. For example, each muscle cell in your body is designed to contract, while each pair of guard cells in a leaf are designed to open and close small pores on the leaf's surface. Groups of specialized cells form tissues that carry out certain tasks, and several types of tissue join to form organs. Cardiac muscle tissue forms your heart, while leaf tissues form the tree's leaves. Organs work together in groups of organ systems, such as your cardiovascular system or the tree's system for photosynthesis. Finally, both you and the tree are organisms made up of collections of organ systems.

Figure 1.1. Children with a tree.

1.1.3 Living Things Gather Matter and Energy

Both you and that tree in your backyard need to gather matter and energy to grow, to move, and to stay alive. The tree can make its own food by using the energy of the Sun to combine carbon dioxide and water. Humans get their matter and energy by eating plants and (for many people) animals. Your cells and the cells of the tree use the nutrient molecules in foods as building blocks or as sources of energy. Both you and the tree take in oxygen and use it to release energy from nutrient molecules.

1.1.4 Living Things Grow, Develop, and Reproduce

The backyard tree was once a small seed. Over time, it increased the number of its cells and grew larger, becoming first a seedling and eventually an adult tree. You began life as a single cell. That cell divided repeatedly, the cells specialized, and a baby was formed. The baby continued to grow and develop through childhood and into adolescence. All living things grow and develop.

The Genesis account of creation describes God's provision for plant reproduction: "The earth brought forth vegetation, plants yielding seed according to their own kinds, and trees bearing fruit in which is their seed, each according to its kind" (Genesis 1:12a). Birds and fish are commanded to reproduce in Genesis 1:22: "And God blessed them, saying, 'Be fruitful and multiply and fill the waters in the seas, and let birds multiply on the earth.' " And men and women were likewise blessed and directed to "be fruitful and multiply" in Genesis 1:28. Life comes from life. You are a new individual organism produced by your two parents. That tree in your backyard is a new individual organism produced by two parent trees.

Although most organisms must have a partner organism to reproduce, some single-celled animals and some plants are able to reproduce on their own. Single-celled animals can divide in two and new plants can sometimes grow from plant parts.

1.1.5 Living Things Use and Pass On Genetic Information

You might look a little bit like your mother and a little bit like your father. When you began life as a single cell, that cell held within it all the instructions it needed to build all the parts of your body. Over the short span of nine months, that single cell divided into countless cells. You have numerous types of cells: skin cells, hair cells, heart cells, brain cells, and more. The instructions for building each type of cell are carried in nearly every cell. Those instructions are sometimes called "genetic information." The first cell that was you got half its genetic information from your mother and half from your father. Much like the single cell that became you, the seed that became the backyard tree also held the genetic information to build all the types of cells it needed. Half the information came from a male tree and half from a female tree. When that tree produces seeds, they hold the genetic information needed to build the cells of a new tree.

1.1.6 Living Things Respond

Living things: 1. are organized 2. gather matter and energy 3. grow, develop, and reproduce 4. use and pass on genetic information 5. respond to stimuli 6. adapt to their environment.

Your body is equipped with several senses that enable you to respond to a stimulus. Colder weather makes you respond by shivering or wearing warmer clothing. Bright sunlight makes you squint or reach for your sunglasses. The pain of a hot sidewalk on the soles of your bare feet causes you to move quickly to a cooler place. That tree in the backyard can also respond to changes in its environment. It can sense light and darkness, gravity, and sources of water, and its direction of growth reflects what it senses.

The backyard tree also works to maintain a healthy range of conditions within its cells. All living things are composed of individual cells. A model of an animal cell is shown in Figure 1.2. For your body to stay alive, your cells must be kept within a certain range of conditions. Your internal temperature cannot be too high or too low. Your cells must have enough water and nutrients, but not too much. Your body must be able to rid itself of wastes. All the systems of your body work together to maintain a healthy range of conditions. This is called *homeostasis*, one of our topics in Chapter 3.

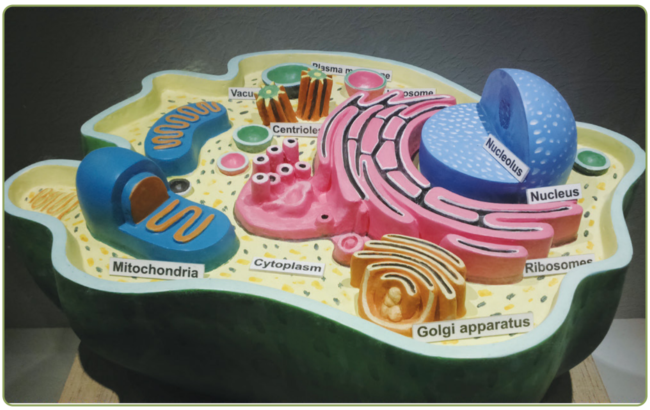


Figure 1.2. A model of an animal cell.

1.1.7 Living Things Adapt to their Environment

The natural environments on our planet are continuously changing. Drought, earthquakes, and forest fires are all processes that cause changes in an environment. As an environment changes, organisms inhabiting that environment can adapt to it by acquiring new traits that make them more fit to live there. For example, if a drought causes plants in the area to begin producing harder seeds, birds with stronger beaks will be better able to crack open and eat the seeds, and thus better able to survive and reproduce in the new environment. Over time, species of birds may be found to have stronger beaks than in the past. The ability to adapt to a changing environment is an important characteristic that enables organisms to survive over centuries on a changing planet. However, sometimes adaptive capabilities can be a problem for humans. An example of adaptation often in the news in recent years is when bacteria develop resistance to antibiotics, rendering the antibiotics less effective. This adaptation has unfortunately happened many times since antibiotics were first developed in the early 1940s.

Learning Check 1.1

1. Why do scientists find it difficult to define life?
2. List and briefly describe six characteristics of living things.

1.2 Defining Science

After years of taking science classes and reading science textbooks, you might think that science is a collection of scientific facts such as these: the Earth is one of eight planets in our solar system; the Earth revolves around the Sun and rotates on its axis; and gravity pulls everything toward the center of the Earth. You would be partly right; it is the business of scientists to discover and collect scientific facts. But they don't collect them just to know a bunch of facts. They use the facts to develop theories. Developing successful theories is the real goal of science.

Figure 1.3. An antique "d'Isle globe" from 1765.

Scientists develop theories to help them think about how the world works. They observe and *experiment* to gather more scientific facts, and they use new scientific facts to improve or to rewrite their theories. Over time, our scientific understanding of the world becomes more and more accurate.

Now we are ready for this formal definition of *science*:

Science is the process of using experiment, observation, and reasoning to develop mental models of the natural world. The mental models scientists develop are called theories.

Theory: A model, representation, or explanation that seeks to account for the related facts and provide means for producing new hypotheses.

A scientific *theory* is a *mental model*—that is, a representation or explanation—describing how some part of the natural world works. You have probably seen and used several physical models that help you to understand the nature of the world. A classroom globe, such as the one pictured in Figure 1.3, is a model that allows you to see the Earth as a whole, since the actual Earth is far too large to observe in that way. Likewise, a model of a human cell like the one shown in Figure 1.2 can help you to understand cell structure. The cell model is big enough to study easily, while an actual cell must be studied through a microscope. Just as a physical model can aid your understanding, a mental model or scientific theory provides a way to think about some aspect of the natural world.

As we discuss in the next section, all scientific theories must possess two key characteristics: they must explain or account for the related scientific facts, and they must provide means for producing new hypotheses.

Learning Check 1.2

1. What is science?
2. Explain what a model is and identify your own example of a model that could be used to explain something.
3. What is a theory?
4. Why do scientists develop theories?

1.3 The Cycle of Scientific Enterprise

You can more easily understand the process of science by studying a scheme called the *Cycle of Scientific Enterprise*, illustrated in Figure 1.4. Developed by master science teacher John D. Mays, this diagram illustrates the idea that scientific knowledge is not gained by simply learning one scientific fact after another. Rather, science is a cyclic process, with each step relying on feedback from the previous step. Let's use the development of cell theory as a case study as we explore each part of the diagram.

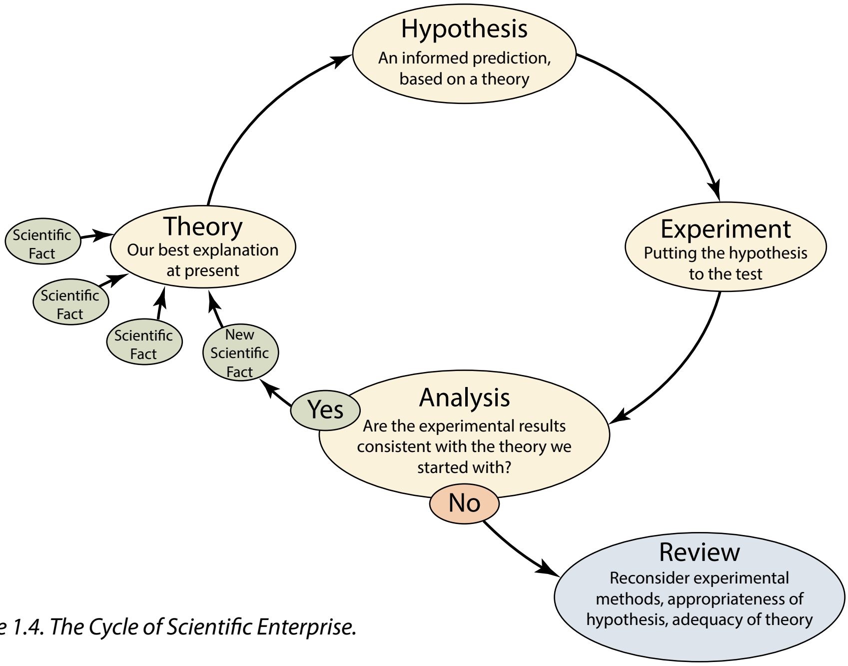
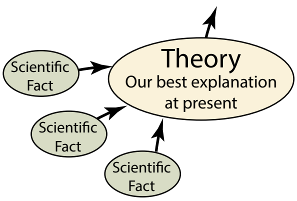


Figure 1.4. The Cycle of Scientific Enterprise.

1.3.1 Theory

Beginning on the left side of the diagram with Theory, recall that a theory is a mental model that helps us to think about how part of the natural world works. It is the business of scientists to develop theories—mental models—that explain most of the known scientific facts in a field of scientific study. Scientific inquiry begins with a theory, and the theory is supported by scientific facts.



Case Study: Part 1

The cell theory, framed after decades of microscopic observations, can serve as our entry point into the Cycle of Scientific Enterprise. According to the cell theory, all organisms are made up of one or more cells.

Science often relies on developments in technology to move forward. For scientists to frame the cell theory, they first had to be able to observe microscopic cells. The story of microbiology begins with Anton van Leeuwenhoek (1632–1723), a Dutch tradesman and scientist. Van Leeuwenhoek learned to use a simple microscope as an apprentice to a cloth merchant in Amsterdam. Leeuwenhoek's microscope, a magnifying glass mounted on a small stand, is pictured in Figure 1.5. In time, van Leeuwenhoek learned to grind lenses and to create high-quality glass spheres that could magnify an object over 200 times (200×). He built small, hand-held microscopes and used them

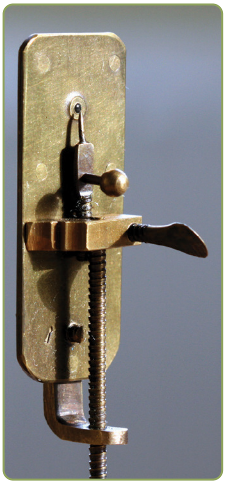


Figure 1.5. A replica of van Leeuwenhoek's microscope.

to observe and describe single-celled organisms, muscle fibers, bacteria, blood flow in capillaries, and anything else he could put under his lenses.

Van Leeuwenhoek sent copies of his descriptions to the famous Royal Society of London, the world's oldest independent scientific academy. Although initially interested in his work, the Royal Society was skeptical when van Leeuwenhoek described single-celled organisms. (He referred to them by the cute name *animalcules*.) When he continued to insist that they existed, the Royal Society sent a team to confirm his observations. Van Leeuwenhoek's claims were verified, and he was appointed as a Fellow of the Royal Society.

Cell theory: All living things are made up of one or more cells.

A contemporary of van Leeuwenhoek, Englishman Robert Hooke (1635–1703), was an architect, natural philosopher, and gifted scientist. He is known for his book *Micrographia*, where he documented and brilliantly illustrated his observations of microscopic samples such as insects, sponges, bryozoans, foraminifera, and bird feathers. Hooke's drawing of a section of cork is shown in Figure 1.6. Hooke contributed the term "cell" to science when he described the box-like structures in thin slices of cork as similar to the cells, or small rooms, of a monastery. Like van Leeuwenhoek, Hooke was a member of the Royal Society and his work encouraged other scientists to take up microscopic investigations.

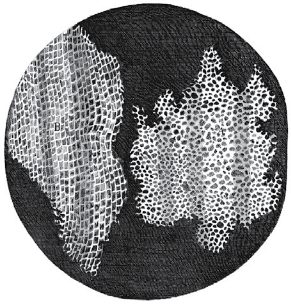


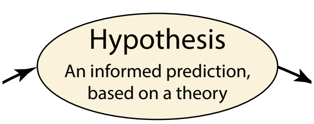
Figure 1.6. Robert Hooke's drawing of cork cells.

Matthias Jakob Schleiden (1804–1881), a German botanist, used a microscope to study numerous plant samples. In time, he realized that all plants, and all parts of plants, are made up of cells. Independently, Theodor Schwann (1810–1882), a zoologist and friend of Schleiden's, reached the conclusion that all animal tissues are made up of cells. Schwann published *Microscopic Investigations on the Accordance in the Structure and Growth of Plants and Animals* in 1839, where he wrote the first statement of the cell theory:

The First Statement of Cell Theory
All living things are made of cells.

So far, our case study has illustrated how a body of scientific facts—all the different observations—give rise to a theory that attempts to explain them.

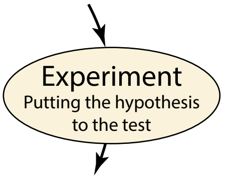
1.3.2 Hypothesis



The next step in the diagram of the Cycle of Scientific Enterprise is Hypothesis. A *hypothesis* is a testable, informed prediction, based on a theory, of what will happen in certain conditions. A strong scientific theory explains all the known facts in a field in a way that can be tested. Without testing, there is no way to determine whether a theory is an accurate description of the workings of the natural world. A well-written hypothesis provides a way to test a theory. A hypothesis is *informed* by the theory that provides the basis for the scientist to predict what will happen if the theory is accurate. A hypothesis must be *testable* for the scientist to use it to determine the accuracy of the theory.

1.3.3 Experiment

Hypotheses are tested through well-designed experiments or observations. A reliable experiment or observation gives clear results and can be repeated by other scientific teams using similar equipment and procedures. All students of science learn through experience that successful experiments can be very difficult to accomplish—so many things can go wrong! Because of this, the scientific community does not rely on the results of a single experiment. If the results can be replicated by other teams, however, they can be considered reliable and are analyzed at the next stage of the cycle.



Case Study: Part 2

The first testable hypothesis suggested by cell theory addressed the origin of new cells. In the 17th century, most people, including scientists, accepted an idea called *spontaneous generation*—the notion that nonliving matter could suddenly produce living matter. In the days before refrigeration, everyone had seen maggots mysteriously appearing on decaying meat, and they thought that the maggots formed spontaneously from the meat. Francesco Redi (1626–1697), an Italian physician,

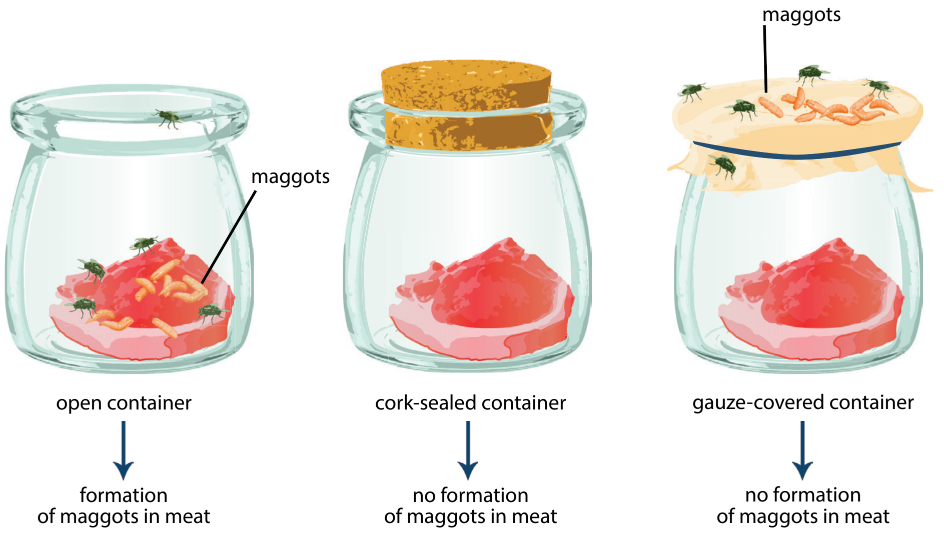


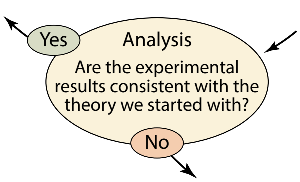
Figure 1.7. Francesco Redi's experiment.

was the first to present experimental evidence that questioned the idea of spontaneous generation. As illustrated in Figure 1.7, Redi placed chunks of meat into three separate jars. He left the first jar open, sealed the second jar with cork, and covered the third jar with gauze. Naturally, the smelly meat attracted flies. The flies laid their eggs directly on the meat in the first jar and on the gauze covering the third jar. They were not attracted to the second, cork-sealed, jar. Soon, the eggs hatched and maggots crawled on the meat in jar one and on the gauze covering jar three. There were no maggots on the meat in either jars two or three. Clearly, the maggots came from the eggs of flies, not from the rotting meat. These results do not support the theory of spontaneous generation.

Louis Pasteur (Figure 1.8), a French chemist and microbiologist, designed and completed further experiments that clearly showed that not even the simplest of organisms—bacteria—come come from nonliving matter. With the work of Pasteur and Redi showing that life comes from life, a hypothesis might be written stating, "If all living things are made up of cells, then all living cells must come from pre-existing cells." Experimental work throughout the 1850s led biologists to determine that new cells come from either the division or the joining of previous cells.

Figure 1.8. French chemist and microbiologist Louis Pasteur (1822–1895).

1.3.4 Analysis



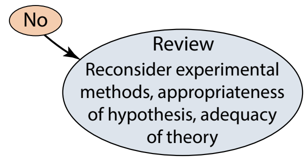
A theory is only useful if it allows scientists to make correct predictions about the natural world. In the next step of the Cycle of Scientific Enterprise, scientists analyze the results of an experiment to decide whether those results support the predictions made in the hypothesis. If the hypothesis is supported, then the theory that it is based upon is strengthened. Well-supported theories consistently lead scientists to correct predictions that are supported by experimental results.

When a hypothesis is supported, the experimental results add more facts to those that the theory explains. We can say that the theory has been strengthened by the addition of the new facts. Notice that we do not say that the theory has been proved. Theories are not truth claims; they are models that may be useful or not useful, more accurate or less accurate. We discuss this idea more deeply later in this chapter.

1.3.5 Review

What happens if experimental results do not support the hypothesis? What do such unexpected negative results mean? When the results of an experiment do not support the predictions made by the hypothesis, the scientist must work backwards through the process, reviewing the experiment, the hypothesis, and the theory to locate the misunderstanding.

Experiments are notoriously difficult to perform without error. Mistakes can be made anywhere along the way, especially in the accuracy of measurements. Review of unexpected results begins with a close look at measurements and measurement techniques. If, after careful review and comparison with the results of other experiments, the experimental results seem valid, the scientist reconsiders the hypothesis.



Review of the hypothesis means evaluating whether it accurately reflects the consequences of the theory. Is the theory correctly understood? If the experiment and the hypothesis both pass inspection, then the scientist must reconsider the theory.

Review of a theory is a big deal. Theories take years or even decades of validation to be accepted as our most accurate explanation of how the natural world works. Even so, if a theory does not account for experimental results, more work is needed. When enough evidence is gathered, scientists will work toward either modifying or replacing the theory.

Case Study: Part 3

The cell theory originally stated:

All living things are made of one or more cells.

The experiments of Redi, Pasteur, and others added evidence that allowed the theory to be expanded to include:

All living cells arise from pre-existing cells by division.

Following further technological development and more observation, experimentation, and reasoning, the theory now includes:

The cell is the fundamental unit of structure and function in all living organisms. The activity of an organism depends on the total activity of independent cells.

The cell theory has been strengthened significantly since the time of Schleiden and Schwann.

Learning Check 1.3

1. What is the difference between a theory and a hypothesis?
2. What are two major characteristics of a successful scientific theory?
3. Describe the observations that led to the first statement of the cell theory.
4. What is the purpose of an experiment?
5. If an experimental result fails to support the hypothesis, how do scientists respond? Describe the steps in the review process and the order in which they are taken.

1.4 Experiments and the Scientific Method

When Louis Pasteur conducted his classic experiment that refuted spontaneous generation and firmly established cell theory, he also solidified the basic steps of the modern *scientific method*. The scientific method describes how to conduct valid experimental research. As we have noted before, experiments are quite difficult to perform without making mistakes. A well-laid out plan helps to reduce experimental error. Table 1.1 describes the steps of the scientific method beside Pasteur's bacteria experiment.

The scientific method is designed to provide an objective, standardized approach to conducting experiments. It is not, however, the only way that scientific research is carried out. In addition, scientists use mathematics, reason, observation, deduction, and demanding investigations to make discoveries.

Step	Task	Remarks from Pasteur's Bacteria Experiment
1	State the problem.	During the 19th century, makers of French wine were troubled by several wine diseases that caused the drink to become sour, bitter, or flavorless. Napoleon III requested that Louis Pasteur study the problem.
2	Research the problem.	Pasteur inspected wine from various locations under his microscope and discovered that they all contained tiny living things we now know as bacteria. It was unclear to the wine makers whether the bacteria caused the spoiled wine, or the spoiled wine produced the bacteria as a side-effect.
3	Form a hypothesis.	Pasteur's hypothesis was that the bacteria in the wine came from bacteria in the atmosphere.

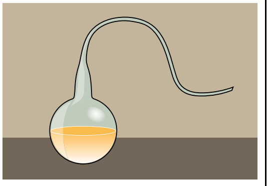
Step	Task	Remarks from Pasteur's Bacteria Experiment
4	Conduct an experiment.	To test his hypothesis, Pasteur prepared a nutrient broth and placed equal amounts into two long-necked flasks. One flask had a straight neck and the other a bent or S-shaped neck. Pasteur boiled the broth in the flasks to kill any living matter. He then left the flasks to sit exposed to air at room temperature. 
5	Collect data.	After several weeks, Pasteur observed that the broth in the straight-neck flask was cloudy and discolored, but the broth in the curved-neck flask was unchanged.
6	Analyze the data.	Microscopic analysis showed bacteria in the broth from the straight-neck flask, but not in the broth from the curved-neck flask.
7	Form a conclusion.	Air was free to enter both flasks, but the S-shaped neck trapped bacteria while the straight neck allowed bacteria to fall into the broth. Bacteria that fell into the nutrient broth were able to reproduce and cloud the broth. The broth that was kept free of bacteria did not spontaneously produce bacteria.
8	Repeat the work.	Although Pasteur repeated his work under different conditions and got the same results, this step means that other teams of scientists must be able to conduct the experiment and get the same results for the work to be considered valid.

Table 1.1. The scientific method with application to Pasteur's experiment.

Learning Check 1.4

1. How does the scientific method relate to doing experimental research?
2. List several other methods for doing science besides experimental research.
3. What is the relationship between a scientist's hypothesis and the scientific method?
4. What is meant by the phrase "repeat the work" in the scientific method?
5. Why is it difficult to analyze experimental results?

1.5 Facts and Theories

Before 1850, people believed that disease was caused by airborne filth and decay, an imbalance of "bodily fluids," or even the poor moral values of an individual. Although they knew that germs existed, they believed that disease causes the presence of germs rather than that germs cause disease. People thought that germs appear in diseased flesh by spontaneous generation or that germs are attracted to disease. Scientists explained these beliefs about disease through the miasma theory, the humoral theory, or the contagionism theory. All these scientific facts about disease proved to be incorrect when improvement of the microscope and development of clear, repeatable experimental techniques produced enough new facts to support the germ theory of disease. Eventually, the germ theory was so well supported that previous theories were abandoned by the scientific community. This example illustrates how scientific facts are revised when new information comes to light. Both facts and theories change when the Cycle of Scientific Enterprise offers new evidence.

A scientific fact is a statement, supported by a lot of scientific evidence, that is correct so far as we know.

A *scientific fact* is a statement, supported by a lot of scientific evidence, that is correct so far as we know. Scientific facts can change as new evidence is obtained. Since scientific facts can change, they are not regarded as "absolute truth." We discuss truth claims in the next section. Scientific facts, however, represent what we suppose at this time to be correct.

The goal of science is to develop accurate theories—successful mental models of how the natural world works. As we've seen in our exploration of the Cycle of Scientific Enterprise, a collection of scientific facts (microscopic observations of cells) leads to the formulation of a theory (cell theory) that explains the scientific facts. The theory provides the base for a hypothesis (new cells arise from preexisting cells) that can be tested. Experimental data provide new facts (cell division) that lend further support to the theory. The successful theory ties scientific facts together and explains them in a model or representation.

These are the key points that define a theory:

A theory is a representation of how part of the natural world works.

Theories are "mental models."

Theories should account for the known facts (so far as possible).

Scientific theories must enable scientists to formulate new hypotheses.

People commonly refer to theories and hypotheses interchangeably. For example, if I find several cupboard doors open in the kitchen, I might incorrectly say, "I've got a theory about who left the cupboard doors open. I think my careless son did it." This statement, however, is not a theory. It's a hypothesis based on my understanding (theory) of my son and his personality and habits. In our cell theory example, a portion of the theory states that all living cells arise from pre-existing cells by division. We can make a prediction based on this theory: We should find dividing cells in a fast-growing portion of a plant. This prediction is a hypothesis that can be tested. Observation of onion root tips under a microscope, shown in Figure 1.9, indeed reveals cells in various stages of division.

The history of science strongly suggests that today's right answer is almost always tomorrow's wrong one; science does not trade in eternal truths, but in temporary approximations.

—Jim Endersby in A Guinea Pig's History of Biology

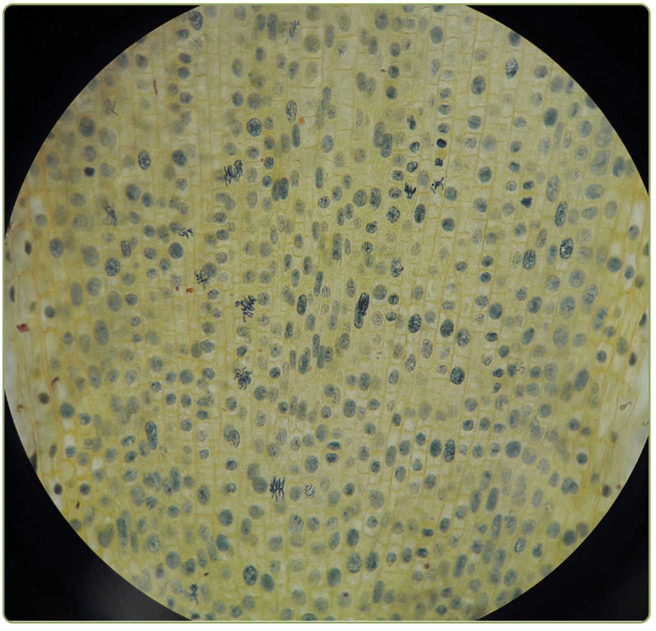


Figure 1.9. Analysis of these cells on the tip of an onion root reveals that the cells are actively dividing.

Because theories are not just hunches or wild, untested ideas, it is important that we speak correctly about them. It is incorrect to say that new data either prove or disprove a theory. Rather, theories are supported, or they are not supported, by experimental data. It is also inappropriate to speak scornfully of theories. Instead, we recognize that theories often take decades to develop and that widely accepted theories have produced supported hypotheses repeatedly over time. Finally, theories are not truth claims; they are models of nature that can be considered accurate if they are well-supported. Theories are constantly reviewed and even revised as new information becomes available. Developing theories that accurately model nature is what science is all about.

Learning Check 1.5

1. What is a scientific fact?
2. Are scientific facts true? Explain.
3. If you hear someone say, "We don't need to believe that; it's just a theory," how could you respectfully explain why this statement is inappropriate?
4. How does a theory become widely accepted?

1.6 Ways of Knowing Truth

If theories and scientific facts are not truth claims, what is the difference between scientific facts and truth? We have learned that scientific facts are propositions gathered through observation, experiments, and reasoning that are correct so far as we know. Accepted scientific facts are supported with much evidence, but they can and do sometimes change when new data lead to new discoveries. *Truth*, however, is permanent. Truth is true for all time, in all places, and for all people. Truth can be defined this way:

Truth is the way things really are.

According to traditional teachings in philosophy and theology, we can know truth through direct observation, valid logic, or divine revelation.

1.6.1 Direct Observation

Truth learned through direct observation is truth that we possess through our own experience. I can make the following truth claim: I am typing these words on my personal laptop. I know this is true because it is obvious to me from my own direct experience. You know many things to be true because of direct, first-hand knowledge. You know the truth about where you live, how many pets you have, and whether you brushed your teeth before going to bed last night.

1.6.2 Valid Logic

Traditional philosophy describes another way of knowing truth: valid reasoning (logic) based on true premises. One form of logical reasoning is called a *syllogism*. A syllogism is a series of two or more statements, called *premises*, followed by a conclusion.

Consider this example involving an elephant, pictured in Figure 1.10:

Premise 1:	All elephants have trunks.
Premise 2:	Ellie is an elephant.
Conclusion:	Ellie has a trunk.

According to formal logic, if the two premises are true, and if the logic is valid, then the conclusion must be true. In the example above, the logic is valid: Ellie the elephant has a trunk.

Here is an example of logic that is not valid, that could involve an animal like the checkered elephant shrew, shown in Figure 1.11:

Premise 1:	All elephants have trunks.
Premise 2:	Ellie has a trunk.
Conclusion:	Ellie is an elephant.

This argument is not valid, because tapirs, anteaters, coatis, and elephant shrews are also animals that have trunks. Ellie could be any animal with a trunk.

Formal logic is not something that most people use every day, but if we do use it, and if we reason with valid logic from true premises, then our conclusion must be true.

Figure 1.10. An African elephant.

Figure 1.11. A checkered elephant shrew.

1.6.3 Divine Revelation

The third way that we can know truth comes from Christian theology. God reveals truth to us through his written Word and through his creation. Truth gained through the reading of God's Word is known as *Special Revelation* and truth gained through observation of creation is known as *General Revelation*. Because the Bible claims to be inspired by God in verses such as 2 Timothy 3:16: "All Scripture is breathed out by God…," Christians believe it to be true. Passages such as 2 Peter 1:16: "…but we were eyewitnesses of his majesty," claim to be telling truth from direct observation. The Bible also teaches, in verses such as Psalm 19:1, "The heavens declare the glory of God," that his creation reveals truth. We can know truth through God's Word and through God's works.

In summary, we can know truth in three ways. From philosophy, we can know truth by direct observation (first-hand experience) and by valid reasoning based on true premises. From theology, we can know truth by Special Revelation, through reading God's Word, and by General Revelation, through observation of God's creation.

1.7 The Nature of Scientific Knowledge

Scientists are in the business of searching for theories that accurately model nature. Through the process described in the Cycle of Scientific Enterprise, those theories tend to become more accurate over time. However, scientific theories are not truth claims. Because people often mistakenly believe that scientists claim their theories are the truth, they may become upset if it appears that a scientific model is in conflict with the Bible. But there cannot be a conflict between belief in God and study of the world God made.

Scientists hope and believe that over time this theoretical knowledge gets closer and closer to the truth.

We must keep in mind that scientific knowledge is a different kind of knowledge than the truth gained by divine revelation, by valid logic, and by direct observation. We know that truth, or the way things really are, is permanent. Scientific knowledge, however, is subject to change when new contradictory evidence is discovered. Scientific facts are correct so far as we know, and theories are the best explanations of the scientific facts we currently have. We need to recognize that while God's Word and his works communicate eternal truth, scientists work to develop provisional, theoretical knowledge. Scientists hope and believe that over time this theoretical knowledge gets closer and closer to the truth.

Learning Check 1.6/1.7

1. Is science in the business of making truth claims? Explain your answer.
2. Define truth.
3. List five examples of truths that you know from the obviousness of your own direct experience.
4. List five examples of truths revealed in the Bible. Write down the exact quotation, along with the citation.
5. Describe the three ways of knowing truth.
6. How do scientists understand the relationship between theories and truth?

1.8 The Scale and Goals of Life Science

1.8.1 Large and Small

Let's take another look at Psalm 33:6: "By the word of the Lord the heavens were made, and by the breath of his mouth all their host." The phrase "all their host" includes a very broad range of life! The smallest known single-celled organism, *Mycoplasma gallisepticum*, shown in Figure 1.12, is a single-celled parasitic bacterium that measures only 0.0001 mm in diameter—only about one fifth the wavelength of green light. If asked what the largest organism is, you might guess the blue whale or the giant redwood tree, but the correct answer is surprising. The largest living thing on Earth is a specimen of honey fungus growing in Oregon, *Armillaria ostoyae*. This organism covers over 3.5 square miles! Shown (in part) in Figure 1.13, this fungus has three main parts: large clumps of yellow-brown mushrooms above ground, black root-like underground *rhizomorphs*, and an underground network of tubular filaments called *mycelia*. This massive fungal growth is considered to be an individual organism because its cells are genetically identical, they can communicate with each other, and they have a common purpose. In addition to the astounding variety and size of individual organisms, the scale of life science ranges from single organic molecules to the entire biosphere—the parts of Earth inhabited by living organisms.

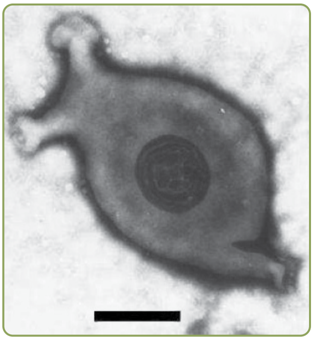


Figure 1.12. Negatively stained Mycoplasma gallisepticum. *For reference, the black bar in the image is only 140 nanometers long.*

Figure 1.13. Small portion of Armillaria ostoyae, *a honey fungus in Oregon that has grown to cover over 3.5 square miles.*

Let's Talk About Scientific Measurements and Units

Two important skills for every scientist are making accurate measurements and correctly using units of measure. We have talked about how difficult it is to perform a precise experiment, and inaccurate measurement is often the culprit when things go wrong. Understanding scientific units of measure takes some study and practice.

Students in the United States have grown up with an unwieldy unit system that uses different units of measure for different sizes of objects. To measure distance, we may use inches, feet, yards, or miles. To measure volume, we may use teaspoons, tablespoons, ounces, pints, quarts, or gallons. Having so many different units means that we must also have many numbers that relate the units to one another: 12 inches in a foot, 128 ounces in a gallon, 5,280 feet in a mile, and so on.

Unit	Symbol	Quantity
meter	m	distance
kilogram	kg	mass
second	s	time
ampere	A	electric current
kelvin	K	temperature
candela	Cd	luminous intensity
mole	mol	amount of substance

Unit	Symbol	Quantity	Derivation
joule	J	energy	$\frac{kg \cdot m^2}{s^2}$
newton	N	force	$\frac{kg \cdot m}{s^2}$
cubic meter	m^3	volume	$m \cdot m \cdot m$
watt	W	power	$\frac{kg \cdot m^2}{s^3}$
pascal	Pa	pressure	$\frac{kg}{m \cdot s^2}$

Scientists worldwide use a much simpler system; the International System of Units, called the *SI System*. Americans often refer to it as the *metric system*. The SI System is made up of seven *base units*, one main unit of measure for each type of quantity. The seven base units are shown in the first table. Units that are made up of combinations of the seven base units are called *derived units*. Some SI derived units are listed in the second table. Metric prefixes, multipliers for larger quantities and fraction prefixes for smaller quantities, scale the main units up or down. The third table lists common metric prefixes.

You are already familiar with the SI unit for time, the second. In order to help you understand some of the other base units, let's make some comparisons with the units you are already familiar with. The meter, the SI unit of distance, is just a little longer than a yard, which you know is 3 feet long. Since 1983, the meter has been defined as the distance light travels in a vacuum in exactly 1/299,792,458 seconds. The kilogram, the SI unit of mass, weighs about 2.2 pounds on Earth. A temperature change of one Kelvin, the SI unit of temperature, is equal to a temperature change of one degree Celsius. Both are almost double the change in temperature represented by one degree Fahrenheit. Room temperature on these scales is 72°F, 22.2°C, and 295.4 K.

As a student of science, you need to know common units of measure, common prefixes used in the metric system, and common "conversion factors" for changing from one unit of measure to another. The tables displayed in this box can be used for reference until you have memorized these units.

	Prefix	Symbol	Meaning	Examples of usage
Multiples	kilo–	k	1,000	One kilojoule is 1,000 joules. There are 1,000 joules in one kilojoule, so 1,000 J = 1 kJ.
	mega–	M	1,000,000	One megawatt is 1,000,000 watts. There are 1,000,000 watts in one megawatt, so 1,000,000 W = 1 MW.
Fractions	centi–	c	1/100	One centimeter is 1/100 of a meter. There are 100 centimeters in one meter, so 100 cm = 1 m.
	milli–	m	1/1,000	One milligram is 1/1,000 of a gram. There are 1,000 milligrams in one gram, so 1,000 mg = 1 g.
	micro–	μ	1/1,000,000	One microliter is 1/1,000,000 of a liter. There are 1,000,000 microliters in one liter, so 1,000,000 μL = 1 L.

1.8.2 From Single Molecules to Organisms

All known living organisms are made up of molecules called *organic compounds*—chemical compounds built around carbon atoms. The four categories of organic compounds are:

- *amino acids*—the building blocks of proteins
- *nucleic acids*—DNA and RNA
- *carbohydrates*—sugar, starch, and cellulose or wood fiber
- *lipids*—fats and hormones.

Organic compounds only come from living things.[1] Organic compounds make up cells, the basic unit of all life. The growth and development of a single cell, the fertilized egg, into a newborn infant is a marvelous event that was described by David in Psalm 139:13–16, "For you formed my inward parts; you knitted me together in my mother's womb. I praise you, for I am fearfully and wonderfully made. Wonderful are your works; my

1 There are a few known exceptions to this statement. One is the existence of interstellar methane. Another is that amino acids have been produced from simpler compounds under intense laboratory conditions. Additionally, methane and maybe ethane have been found on Mars and some of Saturn's moons. These compounds may or may not be the product of living things.

soul knows it very well. My frame was not hidden from you, when I was being made in secret, intricately woven in the depths of the earth. Your eyes saw my unformed substance; in your book were written, every one of them, the days that were formed for me, when as yet there was none of them."

1.8.3 From Ecosystems to the Biosphere

Single organisms can't survive on their own. They rely on other organisms and on the physical environment to grow and to reproduce. Local groups of the same species of organism form *populations* and different populations interact to form *communities*. Communities live within an *ecosystem*, while all the ecosystems on Earth together make up the *biosphere*.

All organisms must have adequate resources in order to live. Although living things depend on their environment for survival, their behavior also changes their environment. As you study how organisms get what they need to survive, you will learn about energy flows, nutrient cycles, population interactions, and how ecosystems change over time.

1.8.4 The Goals of Life Science: Food, Energy, Health, and Environment

Life science is the branch of science most closely related to our daily lives. It seeks to answer questions that come from a natural curiosity about the living world.

Everyone in the world must eat, so we have questions about food: What are the physical benefits of different foods? How can crop yields be increased? What roles do proteins play in the cells of the body? Life science helps us to find new ways to raise crops and process food.

As we try to understand living organisms better, some of our questions are about energy: How do plants obtain energy without eating? How do our bodies convert food into the energy we need? What molecules are involved in delivering energy to different parts of the body? Life science helps us to design more effective biology-related products.

We seek to improve human health and understand inheritance: How do our bodies fight disease? How do organisms maintain homeostasis? Why do children look like their parents? Life science helps us improve medical treatments and therapies.

Finally, we are increasingly concerned today about how our actions affect the environment: How can we be responsible stewards of this planet and its millions of living species? How do we obtain the energy we need without producing pollution or causing other harm to the environment? In what ways do different life forms interact with each other and the environment? Genesis 2:15 tells us that "The Lord God took the man and put him in the garden of Eden to work it and keep it." Today, we understand the garden we need to care for to be the entire creation. Life science helps us understand how to be good stewards of what God has given us.

Learning Check 1.8

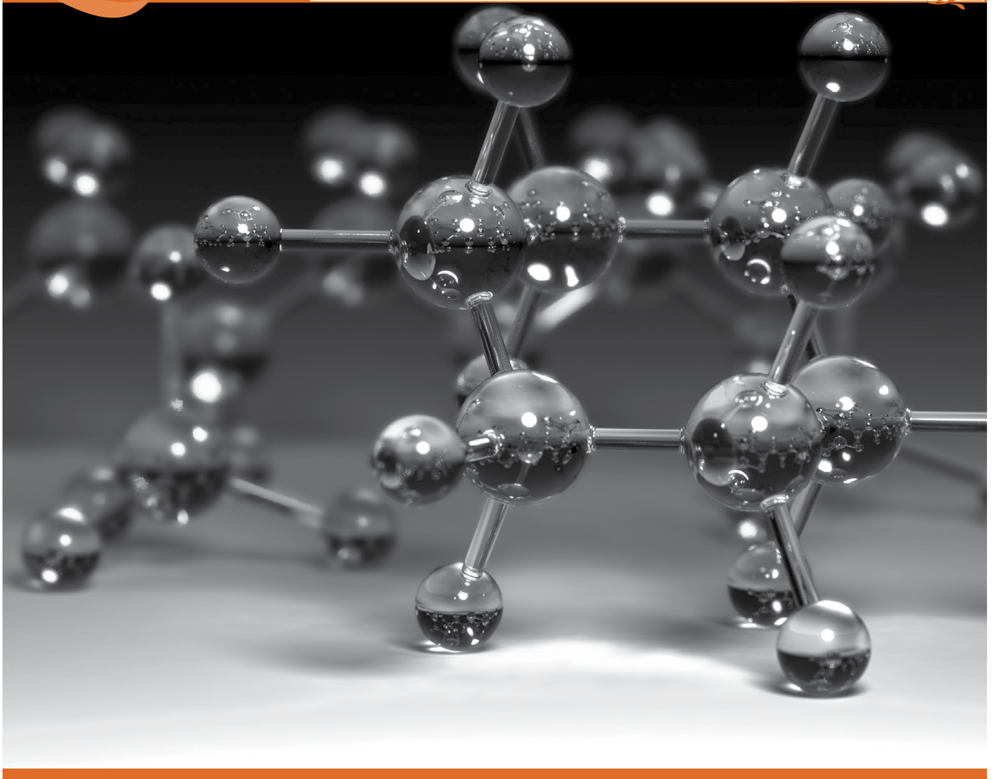
1. Describe the scale of life science.
2. Write at least two questions you have that could be answered through life science.
3. List four goals of life science.

Chapter 1 Exercises

Answer each of the questions below as completely as you can. Write your responses in complete sentences.

1. List and briefly describe the series of characteristics scientists use to identify life.
2. Describe each of the main steps in the Cycle of Scientific Enterprise. Define each term and explain how the terms relate to one another.
3. Write a paragraph or two explaining the difference between scientific theories and truth.
4. Explain the purpose for the sequence of steps in the scientific method.
5. Describe Louis Pasteur's contribution to the scientific method.
6. Explain why it is inappropriate to ridicule a scientific theory by calling it "just a theory." In your explanation, describe appropriate ways to speak of scientific theories.
7. State the contributions of Anton van Leeuwenhoek, Robert Hooke, Matthias Jakob Schleiden, and Theodor Schwann to the cell theory.
8. Describe the importance of Francesco Redi's and Louis Pasteur's experiments.
9. Describe the keys ideas in the cell theory.

Chapter 2 From Molecules to Cells



The Building Blocks of Life

This image of a 3D model of organic molecules was created using an app for 3D computer graphics and computer-aided design. Organic molecules are invisible, not only to the naked eye, but also to standard light microscopes. For decades, scientists have inferred the structure and behavior of molecules through observation and experimentation. Since molecules are too small to be seen, students study them by using physical and mathematical models. As the technology of microscopes develops, the invisible world is being brought into focus. Scanning tunneling microscopes, noncontact atomic force microscopes, and quantum microscopes create images of the ever smaller. In 2013, physicists at the Department of Energy's Berkeley Lab in California took the first high-resolution images of a molecule making and breaking chemical bonds. They were startled by the similarity between the images of the molecules and their textbook diagrams. New support for a theory through newly gained data is an example of the Cycle of Scientific Enterprise in action.

OBJECTIVES

After studying this chapter and completing the exercises, you should be able to do each of the following tasks, using supporting terms and principles as necessary.

1. Identify the basic building blocks of cells.
2. Name and describe the four basic types of organic molecules used by cells.
3. Provide evidence that living things are made of cells (either one cell or many different numbers and types of cells).
4. Describe the function of a cell as a whole and ways the parts of cells contribute to the function.
5. Describe the primary role of the nucleus, chloroplasts, mitochondria, cell membrane, and cell wall.

VOCABULARY TERMS

You should be able to define or describe each of these terms in a complete sentence or paragraph.

1. cell
2. cell membrane
3. cell wall
4. chloroplast
5. compound
6. cytoplasm
7. cytoskeleton
8. element
9. enzyme
10. eukaryotic cell
11. hormone
12. mitochondrion
13. nucleus (of cell)
14. organelle
15. organic molecule
16. prokaryotic cell
17. ribosome

2.1 A Short Chemistry Lesson: Part 1

2.1.1 Seeing Tiny Things

What is the smallest thing that you can see? If your eyesight is normal, and you aren't using any tools, such as magnifying glasses, microscopes, or telescopes, you can see objects as small as about 0.1 millimeter (0.1 mm) or 100 micrometers (100 μm). You can see single human hairs and lice. But you can't see what human hairs and lice are made of. You can't see the building blocks of matter with your naked eyes.

The smallest things you can see with the unaided eye are about 0.1 mm in size.

Magnifying tools use one or more special lenses to bend light in a way that increases the size of the image that is sent to your eye. Using a standard optical microscope, you can see objects as small as 1 μm. You can look at bacteria, blood cells, and the compound eyes of flies

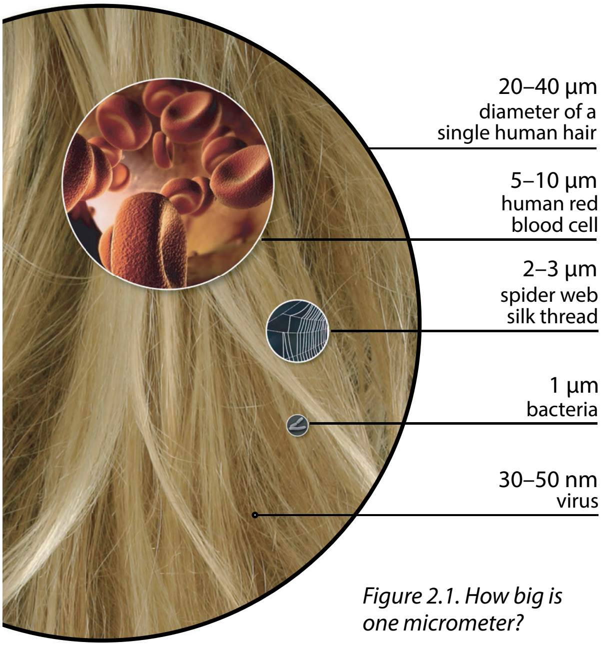


Figure 2.1. How big is one micrometer?

with a standard microscope. You can get a little closer to the building blocks of matter by studying animal and plant cells, but you still can't see much detail inside those cells, and you can't see the building blocks of those cells. Matter is made of molecules, and molecules are composed of individual atoms. Both atoms and molecules are particles too tiny to see, even with high-powered light microscopes.

A new invention, the microsphere nanoscope, uses a transparent globe of silicon dioxide to create visible images of objects as small as 50 nanometers (50 nm). Scientists can see much more detail inside cells with this tool, but the building blocks of matter are smaller yet. Figure 2.1 shows that single-celled bacteria are about one micrometer (1 µm) in size. This is about 20 times the size of a 30–50 nm virus particle (a virion).

Human hair, lice, bacteria, blood cells, and the compound eyes of flies are all made of matter. In fact, everything that takes up space and has mass is made of matter. Matter, whether living or nonliving, is made of atoms and molecules and these particles follow the laws of chemistry. For this reason, we begin our study of life science in this chapter with a couple of short chemistry lessons.

2.1.2 States of Matter

Matter exists in three basic states: solid, liquid, and gas (or vapor). It is easy to find examples of all three states. If you consider the image of Earth in Figure 2.2, you can quickly classify solid land, liquid oceans, and gaseous atmosphere. Water, a compound that is necessary for life, is also easy to find in solid (ice), liquid (water), and gaseous (water vapor) states. The state of matter depends on the amount of energy in the particles of that matter. You can measure the amount of energy in the particles of matter as temperature. The more energy the particles have, the higher the temperature of the substance is. Different

Figure 2.2. Beautiful Earth.

substances melt or freeze at different temperatures. For example, while water freezes at 0°C and boils at 100°C, ethanol, a type of alcohol, freezes at –114°C and boils at 78.4°C.

The particles that make up matter—atoms and molecules—are always moving. Particles in a solid are strongly attracted to one another, so they vibrate in place. Solids, such as ice cubes, have a fixed volume and a fixed shape. Adding enough heat energy to a solid causes it to melt—the particles break free of each other and move around one another. If you put a pan of ice cubes on the stove and turn it on, the solid cubes gain this energy from the hot burner, melt, and become liquid water.

Figure 2.3. Water on waxed paper.

Liquids have a fixed volume and they take the shape of their container. Although the particles have enough energy to remain free of each other and move around, they are still loosely attracted to one another and they tend to cling together. This clinging is responsible for the way water beads up when placed on waxed paper, shown in Figure 2.3. If you continue to heat the liquid water on your stove, the particles will eventually gain enough energy to vaporize—that is, break completely free from one another, entering the gaseous (or vapor) state.

Gases have no fixed volume and no fixed shape. The particles have so much energy that they fly around, bouncing off each other and the walls of any container. Although you cannot see the atoms and molecules that make up gases, they still have mass and take up space. If you have ever blown up a balloon too much, you know that you can only fit so much gas into the balloon before it bursts.

2.1.3 Atoms and Elements

While all matter is made up of atoms, atoms are not all alike. You probably already know that atoms are made of three smaller particles—protons, neutrons, and electrons. Protons each possess the same amount of positive electrical charge. Electrons each have an equal amount of negative charge, and neutrons have no charge. As illustrated in Figure 2.4, protons and neutrons form the dense nucleus of an atom and electrons race around outside the nucleus.

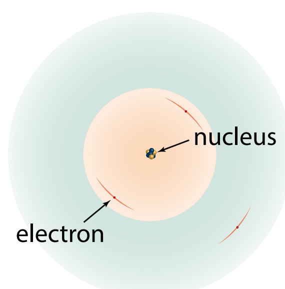


Figure 2.4. Diagram of a small atom (lithium, actually).

The smallest atom, hydrogen, contains one proton. Any atom with one proton is an atom of hydrogen. If an atom contains two protons, it is not hydrogen—it is helium. And an atom with three protons is an atom of

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.0079																	2 He Helium 4.0026
2	3 Li Lithium 6.941	4 Be Beryllium 9.0122											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984	10 Ne Neon 20.1797
3	11 Na Sodium 22.9898	12 Mg Magnesium 24.3050											13 Al Aluminum 26.9815	14 Si Silicon 28.0855	15 P Phosphorus 30.9738	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.9559	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.9380	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.9059	40 Zr Zirconium 91.224	41 Nb Niobium 92.9064	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.82	50 Sn Tin 118.710	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.9045	54 Xe Xenon 131.29
6	55 Cs Cesium 132.905	56 Ba Barium 137.327	71 Lu Lutetium 174.967	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 208.9824	85 At Astatine 209.9871	86 Rn Radon 222.0176
7	87 Fr Francium 223.0197	88 Ra Radium 226.0254	103 Lr Lawrencium 262.11	104 Rf Rutherfordium 261.11	105 Db Dubnium 262.114	106 Sg Seaborgium 263.118	107 Bh Bohrium 262.12	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (281)	112 Cn Copernicium (285)	113 Nh Nihonium (284)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.9077	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolinium 157.25	65 Tb Terbium 158.9253	66 Dy Dysprosium 162.50	67 Ho Holmium 164.9303	68 Er Erbium 167.26	69 Tm Thulium 168.9342	70 Yb Ytterbium 173.04
89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.0359	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium 252.083	100 Fm Fermium 257.0951	101 Md Mendelevium 258.10	102 No Nobelium 259.1009

liquid at room temperature

radioactive

Figure 2.5. The Periodic Table of the Elements.

lithium. The number of protons in the nucleus of an atom determines the identity of that atom. We call the number of protons in an atom its *atomic number*.

An element is a substance composed of atoms with the same atomic number.

An *element* is a substance composed of atoms with the same atomic number. The Periodic Table of the Elements, shown in Figure 2.5, arranges atoms in the order of increasing atomic number, beginning with element 1, hydrogen, and ending with element 118, oganesson. Figure 2.6 shows a single box from the periodic table. Each box provides basic information about one of the elements in the table. The atomic number, the number of protons in one atom of that element, is at the top of the box. The chemical symbol, a one- or two-letter abbreviation for the element's name, is placed in the center of the box. Chemical formulas and chemical equations use the chemical symbols of the elements. Below the chemical symbol is the element's name. The number at the bottom of the box is the element's atomic mass. The periodic table is arranged in vertical columns called *groups* and in horizontal rows called *periods*. The atoms in a particular group have similar chemical and physical characteristics, such as whether they burn or dissolve in water. The first four periods contain the elements that are most important to life science.

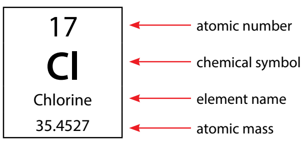
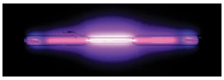
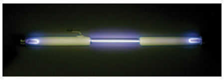
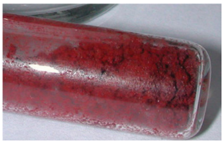


Figure 2.6. A single box in the periodic table.

Currently, the periodic table contains 118 elements. Of those, the first 94 occur naturally on Earth and the remaining 24 have been produced by scientists. Different combinations of six particular elements are most important in living things. These elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—combine to form carbohydrates, lipids, proteins, and nucleic acids. Other elements that are important to living things include sodium, potassium, calcium, iron, and magnesium. Table 2.1 describes the six most important elements.

Element	Description	% of Animal	% of Plant	Image
1 H hydrogen	Hydrogen is a colorless, odorless, tasteless gas that burns in air to produce water. One atom of hydrogen contains one proton and one electron. Hydrogen is the most abundant element in the universe. On Earth, it usually combines with other elements. As the lightest element, hydrogen easily escapes Earth's upper atmosphere.	10%	10%	High-voltage electricity makes hydrogen gas glow blue-violet. 

Element	Description	% of Animal	% of Plant	Image
6 C carbon	Carbon in its elemental form is most well-known as graphite—the soft, shiny, dark gray, greasy-feeling mineral used to make the "lead" in lead pencils, or as diamond—the world's hardest natural material. Carbon joins readily with other atoms to form compounds such as carbon dioxide, calcium carbonate, and fossil fuels such as coal, oil, and natural gas. Carbon atoms can combine in very long chains. Carbon is included in the compounds that make up carbohydrates, proteins, and fats.	19%	12%	A chunk of graphite. 
7 N nitrogen	Nitrogen is also a colorless, odorless, tasteless gas. It is the most abundant element in Earth's atmosphere, about 78% by volume. It is an essential component of genes and proteins.	4%	1%	High-voltage electricity makes nitrogen gas glow violet. 
8 O oxygen	Oxygen, another colorless, odorless, tasteless gas (shown in the model of Figure 2.7), is about 16 times as heavy as hydrogen. Oxygen easily combines with other elements. It is the most abundant element in Earth's crust. Oxygen makes up 21% of our atmosphere by volume. It also makes up 50% of Earth's crust, and 85% of Earth's hydrosphere—oceans, lakes, and other forms of water. Oxygen occurs both as a free element and in many compounds.	63%	77%	High-voltage electricity makes oxygen gas glow blue-violet (the center of the gas tube). 
15 P phosphorus	Phosphorus is not found in its pure, elemental form in nature; its atoms join easily with other types of atoms, forming compounds. Scientists can purify phosphorus in the laboratory. As an element, different forms of phosphorus can be colorless, waxy white, yellow, scarlet red, violet, or black.	< 1%	< 1%	A glass tube containing phosphorus. 

Element	Description	% of Animal	% of Plant	Image
16 S sulfur	Sulfur is a bright yellow solid that forms small crystals in its elemental form. It is the fifth most common element by mass on Earth. You might be surprised to learn that the sulfur you smell in boiled eggs is from a protein compound found in the egg white (not in the yellow egg yolk). Sulfur containing compounds are essential for life.	< 1%	< 1%	Sulfur crystals. 

Table 2.1. Six important elements for life.

Learning Check 2.1

1. What causes matter to change state from solid to liquid or from liquid to gas?
2. What determines the chemical identity of an atom?
3. Using the data from Table 2.1, create a bar chart that compares the percentages of carbon, hydrogen, nitrogen, and oxygen in plants to the percentages of those elements in animals.

2.2 A Short Chemistry Lesson: Part 2

2.2.1 Molecules and Compounds

Each of the six elements described in the table above occur in living organisms as *compounds*—chemical combinations of atoms. Very few elements exist in nature as single atoms. Instead, most atoms join together in groups to form molecules. Two or more of the same type of atom chemically bound together make a molecule of an element, while two or more different types of atoms bound together make a molecule of a compound.

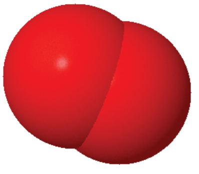


Figure 2.7. A model of the diatomic oxygen molecule, O_2.

In most molecular models, atoms of different elements are assigned certain colors: white for hydrogen, black for carbon, blue for nitrogen, red for oxygen, yellow for sulfur, and orange for phosphorus. The computer-made models shown in Figures 2.7 and 2.8 are "space filling" model—they show how close the centers of the atoms are to one another in the molecule and how much space the molecule occupies. Other types of molecular models (such as the "ball-and-stick" model on the opening page of this chapter) provide different information,

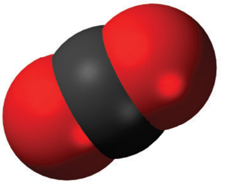


Figure 2.8. A model of a carbon dioxide molecule, CO_2.

such as how the atoms are bonded together in the molecule.

The three gases listed among the six elements that are basic to life, nitrogen (N_2), hydrogen (H_2), and oxygen (O_2), occur naturally in *diatomic* (two-atom) molecules. These two-atom molecules are molecules of elements, because in each pair of atoms the atoms are of the same element.

If an atom of oxygen joins chemically with two atoms of hydrogen, the three atoms form a molecule of water (H_2O). Water is a compound. The compound carbon dioxide (CO_2), shown in Figure 2.8, is made up of one atom of carbon and two atoms of oxygen. A molecule of the simple sugar glucose ($C_6H_{12}O_6$) is a much more complicated compound made of six carbon atoms, 12 hydrogen atoms, and six oxygen atoms, a total of 24 atoms.

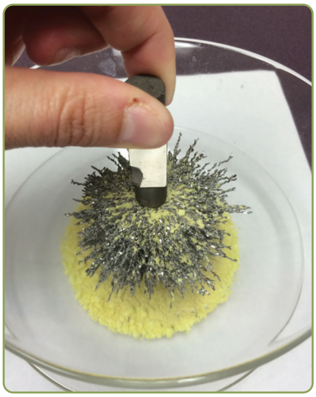


Figure 2.9. Physical separation of iron and sulfur.

Elements that form a compound are not merely mixed together. Stirring up a jar of oxygen and hydrogen only gives you a *mixture* of oxygen and hydrogen. In order for the compound water to form, a *chemical reaction* must take place. A chemical reaction is the making, breaking, or rearranging of the chemical bonds between atoms. Many chemical reactions can only occur if there is a source of energy. Adding a spark to the mixture of oxygen and hydrogen atoms supplies the energy needed to produce water (and the mixture goes BOOM when this happens!).

Figure 2.10. Iron sulfide, FeS.

A compound has properties that are very different from the properties of the elements it is composed of. For instance, at room temperature, both oxygen and hydrogen are gases, but the compound water is a liquid. In Figure 2.9, a student is separating a *mixture* of iron and sulfur with a magnet. This is possible because iron has the property of being magnetic. However, if the mixture is heated a chemical reaction occurs, forming a compound called iron sulfide (FeS), shown in Figure 2.10. Iron sulfide is not magnetic, and the compound cannot be separated with a magnet.

Compounds are *pure substances*. The composition of a pure substance is always the same, all the way down to the level of the molecules that make up the substance.

2.2.2 Chemical Formulas

If you look up the perfect ratio of flour to baking powder for a cake recipe, you find that for one cup of flour you need one teaspoon of baking powder. In a similar way, you have to have exactly two atoms of hydrogen for every one atom of oxygen to make molecules of water. And you need exactly one atom of iron for every atom of sulfur to make iron sulfide. Because atoms always combine in fixed whole-number ratios when they form compounds, we can write *chemical formulas* such as H_2O or FeS to represent units of different compounds.

A chemical formula is made of the chemical symbol of each element in the compound followed by a subscript indicating the number of atoms of that element in one unit of the compound. If there is only one atom of an element, no subscript is needed. The formula for iron sulfide, FeS, shows that one unit of iron sulfide is made up of one iron atom and one sulfur atom. A pile of iron sulfide maintains the 1:1 ratio of one part iron to one part sulfur. The more complex molecule glucose, $C_6H_{12}O_6$, has the atomic ratio of 6:12:6, carbon : hydrogen : oxygen. If you could take a cup of glucose and break every molecule down to its individual atoms, you would have six parts carbon to 12 parts hydrogen to six parts oxygen.

2.2.3 The Amazing Chemistry of Water

Among the many conditions that must be met for life as we know it to exist is the availability of a lot of water. The number of ways water is involved in life is staggering, but two large-scale roles on Earth's surface are to regulate Earth's surface temperature and to transport nutrients. Water can accomplish these tasks because of its remarkable structure. Individual water molecules are *polar*—they are electrically positive on one side or end and electrically negative on the other. An oxygen atom has eight positively charged protons in its nucleus, while a hydrogen atom has only one. As a result, the oxygen atom in a water molecule attracts the negatively charged electrons in the atoms of the molecule more strongly than the hydrogen atoms do. The stronger pull of the oxygen atom causes the electrons in the molecule to shift toward the oxygen atom, making that region in the molecule have a partial negative charge. Since the hydrogen atoms are further from their electrons than normal, they have a partial positive charge. The molecule acts somewhat like a small magnet with positive and negative poles, except that the poles are electrical, not magnetic.

The polar nature of the water molecule makes water behave unlike any other substance. Water possesses a large number of unusual properties that are essential for supporting life.

Figure 2.11 shows a model of several interacting water molecules. The symbols δ+ and δ– show where each molecule has a partial positive charge (at the hydrogen

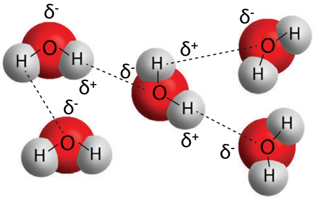


Figure 2.11. Hydrogen bonding.

atoms) or a partial negative charge (at the oxygen atom). The dashed lines show that the opposite charges in different molecules attract each other. The partially positive hydrogen atoms are attracted to the partially negative oxygen atoms in the surrounding molecules.

The polar nature of the water molecule makes water behave unlike any other substance. In fact, the polarity of water molecules gives water a large number of unusual properties that are essential for supporting life:

Figure 2.12. Koi fish in a pond.

Water is an excellent *solvent*. It dissolves more substances than any other solvent known. Water dissolves salts, sugars, proteins, oxygen, carbon dioxide, and many other substances. This property has led to water's nickname as the *universal solvent*. Because it can dissolve so many substances, water is useful for transporting nutrients and for sustaining aquatic life, such as the koi fish in Figure 2.12.

Water displays *capillary action*. Water climbs up small-diameter tubes because the molecules of water are attracted to the molecules of the tube. Plants use capillary action to draw water up the roots and stems to the rest of the plant.

Water has a high *specific heat capacity*. This means that water can absorb a lot of heat energy without becoming much hotter itself. The high specific heat of water reduces

Let's Talk About Antoine-Laurent Lavoisier (Water is not an element!)

The ancient Greeks were curious about the basic building blocks of matter. Some thought that everything was made from combinations of four "elements": earth, air, fire, and water. Centuries of work by scientists taught us not only that the four-elements theory was not correct, but also that none of those substances is elemental. One hardworking scientist who contributed to our understanding of matter was the French chemist Antoine-Laurent Lavoisier (1743–1794).

Lavoisier was encouraged by his father to earn a law degree, but he was more interested in science. He met geologist Jean-Étienne Guettard while at Mazarin College, and after graduation the two worked together on a geological survey of France. Lavoisier realized the importance of taking careful measurements and he was good at analyzing geological samples. The French Academy of Sciences was impressed with his work and elected him to become a member at the age of 25.

When Lavoisier was 28, he married 14-year-old Marie Anne Pierrette Paulze. The figure shows an oil painting of the couple. Madame Lavoisier was intelligent and interested in her husband's scientific work. She drew sketches

of his experiments, helped in the laboratory, and kept records in the laboratory notebooks. She also learned English to help Lavoisier keep abreast of the work of English scientists.

When Lavoisier was appointed as a commissioner of the Gunpowder Commission in 1775, he took up residence and set up his laboratory at the arsenal in Paris. He worked for several hours each day and one full day each week on experiments. On lab day, friends and students joined the Lavoisiers to collaborate on experiments, share a meal, and debate new ideas.

Lavoisier was interested in studying *combustion*, the process of burning. He burned phosphorus and sulfur and learned that they had gained mass in the process. He burned lead calx (now known as lead oxide) and found that air was produced. Lavoisier's carefully measured experiments showed that air was important in combustion. At the time, no one clearly understood that air is composed of several different gases.

In 1774, the French chemist met with the English natural philosopher Joseph Priestley, who had also been experimenting with combustion. Priestley told Lavoisier that he had decomposed mercury calx (now known as mercury oxide) and trapped the gas produced. He found that a candle burned more vigorously in this unknown gas than it did in common air. Lavoisier was interested in Priestley's work, so he repeated the experiment with other metal oxides. Eventually, he concluded that the gas produced in these experiments was also present in common air, mixed with other gases. Air was not an *element*, but a *mixture*. Lavoisier gave the name of *oxygen* to the gas that Priestley had discovered.

Earlier, in 1766, an Englishman named Henry Cavendish had separated a gas that burned well. He called it "inflammable air." Priestley put inflammable air and common air together in a closed container and lit the mixture with a spark. He noticed that a small amount of moisture formed on the glass. Cavendish repeated this experiment and analyzed the moisture. He discovered that it was water, but he thought the water must have been in the air before the spark was applied.

Lavoisier also repeated the experiments with inflammable air and common air, but he came to a different conclusion than Cavendish. He realized that water was not an element, but a compound of oxygen and inflammable air, which we now call *hydrogen*. The spark had provided the energy needed for a chemical reaction between hydrogen and oxygen to occur, and water was the product of that reaction. Lavoisier went on to support his hypothesis by decomposing water into oxygen and hydrogen.

temperature changes in the bodies of animals and plants. It also gives coastal regions mild climates.

Water has a high *heat of vaporization*. It takes a lot of heat energy to evaporate even a little water. This slows the loss of large bodies of water to the atmosphere.

Water has a high *heat of fusion*. A lot of heat energy must be removed before water can freeze.

Water has a high *surface tension*. Because water molecules are polar, the hydrogen atoms of one water molecule are attracted to the oxygen atoms of other water molecules, as illustrated in Figure 2.11. This attraction is called *hydrogen bonding*. Hydrogen bonding causes water molecules to cling together, creating a membrane-like surface. You may have seen small insects walk on the surface of water. They can do this because of water's high surface tension.

Water expands when it freezes. Like most substances, when water cools it contracts, but only until it reaches 3.8°C (about 38°F). Below that temperature, the molecules form a crystal structure, with each molecule bound to four other molecules. This structure takes more space and is less dense than liquid water. Because it is less dense, ice floats on water, as Figure 2.13 illustrates. Ice on the surface of a pond or lake acts as an insulator, preventing the water from freezing solid. If bodies of water froze from the bottom up, all life in them would die.

Figure 2.13. Ice floats on water.

Learning Check 2.2

1. Compare and contrast elements and compounds.
2. Describe how a molecule of an element differs from a molecule of a compound.
3. Explain what must occur for elements to form compounds.
4. What does a chemical formula represent?
5. Discuss the importance of water to life.
6. Describe the structure of a water molecule.

2.3 Organic Molecules

You've probably heard the saying, "You are what you eat." This statement is literally true, as your food is the source of the organic molecules that your cells need. Bread, potatoes, and pasta provide carbohydrates that your body breaks down through digestion into sugars. Oils and butter are sources of lipids and your body breaks them down into glycerol and fatty acids. Meat, eggs, cheese, nuts, and beans are rich in proteins that provide amino acids when digested. Your cells use these organic molecules as building material.

Organic molecules are molecules that contain carbon (C) and hydrogen (H). Carbon atoms are unusual in that they form long chains and ring-shaped structures. The three-dimensional shape of an organic molecule gives it the ability to perform certain functions or tasks. For example, *hormones* have specific shapes that cells recognize, and *enzymes* speed up certain chemical reactions within cells because of their shape.

Organic molecules are molecules that contain carbon and hydrogen.

Simple organic molecules are called *monomers*. "Mono" means one. Cells link monomers together to build *polymers*—macromolecules made of many molecules joined together. Table 2.2 shows four basic types of polymers and the monomers that make them. In the following sections, we discuss each of these important polymers, one at a time.

Macromolecule	Monomer	Polymer
carbohydrate	monosaccharide	polysaccharide
lipid	glycerol and fatty acids	triglyceride
protein	amino acid	polypeptide
nucleic acid	nucleotide	nucleic acid

Table 2.2. Organic molecules and their monomers.

Figure 2.14. Carrots store starch.

2.3.1 Carbohydrates

Carbohydrate molecules are made of carbon, hydrogen, and oxygen atoms in a 1:2:1 ratio. All living organisms use carbohydrates as a source of energy and as a means of storing energy. Carbohydrates also provide structure for woody plants, bacteria, insects, and other animals. *Glucose* (blood sugar) is a simple sugar that our bodies use as an immediate source of energy. Other simple sugars include *fructose*, the sugar in fruits, and *galactose*, the sugar in milk.

Plants link excess glucose molecules into long polymers. These *complex carbohydrates* can be stored as *starch* in seeds, roots, or fruits for later use. Figure 2.14 shows carrots; the extra glucose from a carrot plant is stored in the carrot. Another polymer that plants make is *cellulose*. Plants use cellulose to build strong cell walls.

2.3.2 Lipids

Lipids are a class of organic molecules that includes fats, oils, and waxes. These materials do not dissolve in water. At room temperature, most fats are solid and most oils are liquid. Lipids stored in animals are usually fats, while lipids stored in plants are usually oils. Waxes provide a protective coating for plants and animals and serve as structural material for honeycombs.

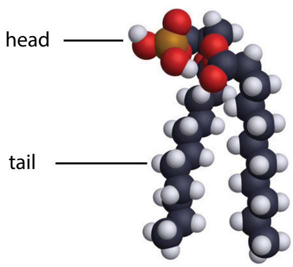


Figure 2.15. A phospholipid molecule.

Fats serve as an important source of energy, as they contain more than twice as much energy per gram as carbohydrates. They protect living organisms from losing too much heat, provide a protective cushion around bones and organs, and store fat-soluble vitamins such as A, D, E, and K. Animals produce the fats they need from the foods they eat.

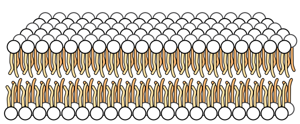


Figure 2.16. The cell membrane is a phospholipid bilayer.

Phospholipids are a special class of lipids that form *cell membranes*, the outer layer or coating that surrounds cells. A space-filling model of a single phospholipid molecule is shown in Figure 2.15. The head of the phospholipid molecule is polar, and thus attracted to polar water molecules, but the tail is not. When phospholipid molecules come together in water, they automatically form two layers with the heads facing out and the tails together, as illustrated in Figure 2.16. (This is one of the handiest—and wonderful—properties in nature because of the way these layers form the membranes surrounding all cells!) This double layer of phospholipid molecules, called a *bilayer*, serves to protect the cell and to keep the internal conditions of the cell stable.

Cells are surrounded by a double layer of phospholipid molecules called the phospholipid bilayer.

2.3.3 Proteins

Protein molecules are the basic building blocks of all living things. Proteins are made of long chains of amino acids. Amino acids are simple organic compounds composed of carbon, hydrogen, oxygen, nitrogen, and sulfur. From 20 amino acids common in humans and animals, cells create different combinations, sequences, and chain lengths that form millions of different proteins. Twelve of those amino acids can be made by the cells inside your body, but the other eight must be obtained from what you eat.

Protein molecules are the basic building blocks of all living things

Proteins are necessary for growth and repair of tissue and other materials in the body. They make up the structural components of claws, hooves, hair (such as the dog hair in Figure 2.17), feathers (such as the down on the ostrich chick in Figure 2.18), and the outer layer of skin. Many hormones are proteins that serve as chemical messengers. Actin and myosin are proteins that support movement within cells and enable our muscle cells to contract. Some proteins, such as hemoglobin, serve as transport molecules. Hemoglobin binds to oxygen and delivers it throughout the body. Enzyme proteins speed up chemical reactions within cells.

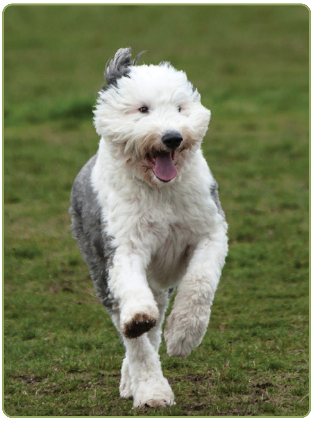


Figure 2.17. A happy, shaggy dog.

Figure 2.18. An ostrich chick.

2.3.4 Nucleic acids

Nucleic acids are information-rich organic molecules found in all living organisms. The two types of nucleic acids, illustrated in Figure 2.19, are *DNA* (deoxyribonucleic acid) and *RNA* (ribonucleic acid). DNA and RNA are the organic molecules in living cells that contain an organism's genetic information, which is passed on from one generation to the next. They are very large molecules, made up of long chains of *nucleotides*. A single nucleotide contains a simple sugar, a phosphate group, and a nitrogenous base. There are five different nitrogenous bases: adenine (A), cytosine (C), guanine (G), thymine (T), and uracil (U). DNA uses the first four bases. In RNA, the base uracil is used in place of thymine.

A single molecule of DNA is made up of two very long strands of nucleotides, while RNA consists of a single strand. The sugar-phosphate groups form the outside edges of the spiraling strand, and the nitrogenous bases extend inward. In DNA, the two strands twist around each other in a shape called a *double helix*. The sequence of the nucleotides serves as the code for making proteins. The code specifies which amino acids are needed to make a certain protein and the order in which the amino acids are to be joined. We dive deeper into nucleotides in a later chapter.

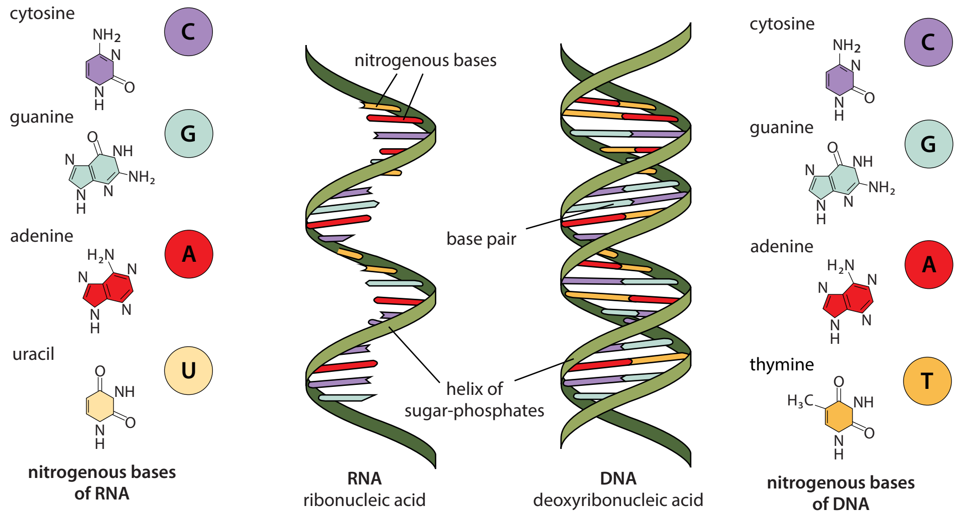


Figure 2.19. Comparing DNA and RNA.

Learning Check 2.3

1. What are two key differences between DNA and RNA?
2. Create a table that includes four organic molecules, their monomers, their polymers, and a short description of each one.

Let's Talk About Cell Surface Area (Why are cells so small?)

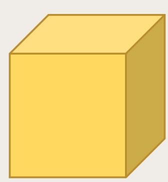
All cells take in nutrients, such as glucose and oxygen, and get rid of wastes, such as carbon dioxide, through their outer surface, the cell membrane. Larger cells need more food and make more waste. As a cell grows larger, its volume increases faster than its surface area. A larger cell must absorb nutrients and expel waste through proportionately less surface area than a smaller cell. The area of a cell's surface compared to the cell's volume limits the cell's size. The ratio of the cell's surface area to the cell's volume is called the *surface area-to-volume ratio*.

Suppose you have a cube-shaped cell that is 3 cm high. To calculate the ratio of surface area to volume for the cell, you use these equations:

$$\text{surface area } (A) = \text{width } (x) \cdot \text{length } (x) \cdot 6$$

$$\text{volume } (V) = \text{width } (x) \cdot \text{length } (x) \cdot \text{height } (x)$$

$$\text{ratio } (R) = \frac{A}{V}$$



Substituting in known values and solving the equations (and ignoring the units in the ratio):

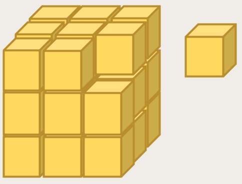
The ratio of surface area to volume for this cell is 2 to 1. This cell has 2 cm^2 of surface area for every 1 cm^3 of volume that it can use for transporting materials.

$$A = 3\ \text{cm} \cdot 3\ \text{cm} \cdot 6 = 54\ \text{cm}^2$$

$$V = 3\ \text{cm} \cdot 3\ \text{cm} \cdot 3\ \text{cm} = 27\ \text{cm}^3$$

$$R = \frac{A}{V} = \frac{54}{27} = \frac{2}{1}$$

Now suppose you divide this cube-shaped cell into 27 1-cm cubes. The total volume for the 27 small cells is the same as for the one larger cell, but notice what happens to the surface area and the ratio of surface area to volume of the group of cells compared to the single large cell.



$$A = 1\ \text{cm} \cdot 1\ \text{cm} \cdot 6 \cdot 27 = 162\ \text{cm}^2$$

$$V = 1\ \text{cm} \cdot 1\ \text{cm} \cdot 1\ \text{cm} \cdot 27 = 27\ \text{cm}^3$$

$$R = \frac{A}{V} = \frac{162}{27} = \frac{6}{1}$$

The ratio of surface area to volume for this cell group is 6 to 1, so this group of cells has 6 cm^2 of surface area for every 1 cm^3 of volume for transporting materials. Compared to the volume, the surface area is three times greater for the smaller cells.

2.4 Cellular Organization and Function

2.4.1 Cell Size

One of the jobs of living cells is to break down nutrients into smaller molecules and then rejoin them to build the molecules needed by the organism. Organic molecules are not living, but the cell that is composed of organic molecules *is* living. The *cell* is the smallest structure that can be said to be alive. Recall from Chapter 1 that it was not until the 1830s that scientists realized that all living organisms are made of cells. Microscopists continued to work through the 1850s, searching for the source of living cells. They eventually realized that cells don't suddenly appear; they come from previously existing cells. This was the beginning of the cell theory.

The cell theory states:

All organisms are composed of one or more cells.

Cells are the basic living unit of structure and function in organisms.

All cells come only from other cells.

Cells do all the work of an organism. Cells manufacture materials, transport substances, communicate with each other, respond to different situations, grow, and reproduce. The smallest living organisms are plants and animals made of a single cell. That cell must do everything for the organism. Larger organisms are made up of many types of cells. Groups of similar cells make up *tissues* and similar tissues make up *organs* that perform different functions for the living organism.

The cell is the smallest structure that can be said to be alive.

Cells vary in size. Bacterial cells are around 1 micrometer (1 μm) in diameter. Human and animal cells average about 10–20 μm in diameter, while plant cells average 50–70 μm. Figure 2.20 shows relative sizes of atoms, molecules, and some different types of cells. Notice that the scale at the base of this figure is *logarithmic*. In this logarithmic scale, each mark represents a number that is 10 times greater than the previous mark. As you learn more about math and science, you will become familiar with other logarithmic scales, such as those that indicate earthquake strength, sound loudness, light intensity, and the pH of solutions.

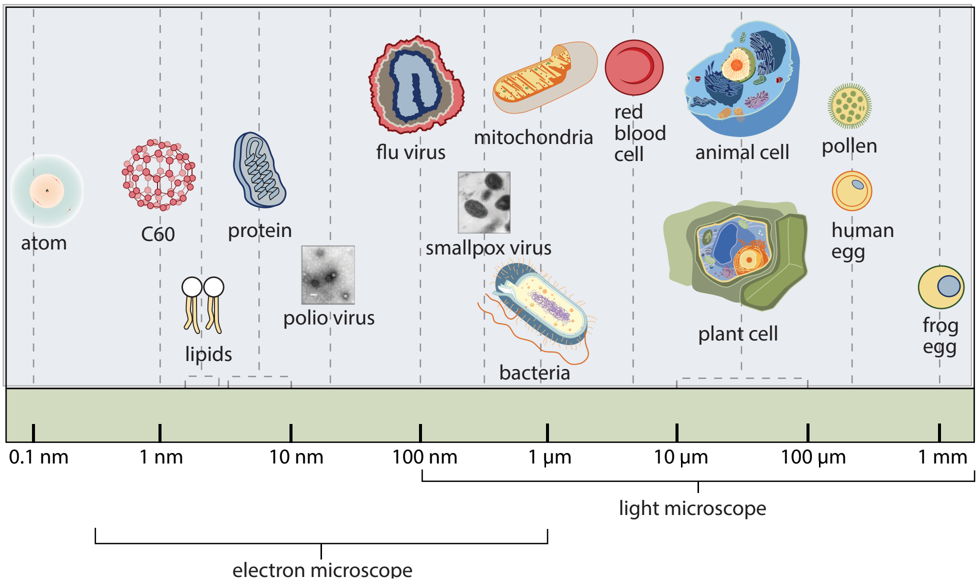


Figure 2.20. Relative sizes of biological components on a logarithmic scale.

You might think that since a single cell is capable of performing all the functions necessary for life, a larger plant or animal could be made of a single larger cell. However, the size of an organism is determined by the number of its cells, not the size of its cells. Living organisms vary in numbers of cells from single identical cells to trillions of specialized cells. Bacteria, archaea, protists, and some types of fungi and algae live their lives as single cells. Some types of algae live in colonies of cells that provide some of each other's needs. The tiny rotifer shown in Figure 2.21, which is a little larger than a protozoan, is a complex creature of about 1,000 cells. A small flowering plant, such as a pansy, has millions of cells. An adult human has between 30 and 40 trillion cells (!) that vary

Figure 2.21. A rotifer.

greatly in design: nerve cells, blood cells, muscle cells, skin cells, and many more.

An adult human has between 30 and 40 trillion cells.

2.4.2 Cellular Organization

We can compare the living cell to a popular 24-hour bagel shop. The shop takes in shipments of coffee beans, flavored syrups, cream, milk, flour, salt, sugar, yeast, cinnamon, poppy seeds, butter, and cream cheese. Chefs use these ingredients to create many types of coffee and a variety of bagels. Some meals are prepared to be eaten in the shop, while others are taken out. Some food is prepared ahead of time so that it is always ready for the customer. Other food is cooked only after it has been ordered. Leftover food and other wastes are placed in trash containers for removal or recycling. Likewise, your cells take in nutrients to create organic molecules. They use some of what they make, send some out to other parts of the body, and store some. They break down wastes, recycle what they can, and remove the rest. And they keep up this activity 24 hours a day, every day.

2.4.3 Cell Classification: Prokaryotic Cells and Eukaryotic Cells

The two basic types of cells are *prokaryotic cells* and *eukaryotic cells*. Organisms composed of prokaryotic cells are called *prokaryotes;* organisms composed of eukaryotic cells are called *eukaryotes*. With a few exceptions, all cells include DNA, *ribosomes*, *cytoplasm*, and are bounded by a cell membrane.

Most bacteria benefit other living organisms.

Modern biologists classify all species in one of three domains: Bacteria, Archaea, and Eukarya. Members of the Bacteria and Archaea domains are single-celled prokaryotes; Eukarya are eukaryotes. We discuss the prokaryotes first here; eukaryotes are described in more detail below.

Prokaryotic cells lack internal membrane-bound structures such as a nucleus and other organelles. Bacteria and Archaea are different from each other in the way that their cell walls and cell membranes are made. Many Archaea can live in hostile environments such as swamps (where there is little oxygen); salty bodies of water; and hot, acidic springs and geysers such as the one shown in Figure 2.22.

Figure 2.22. Grand Prismatic Spring at Yellowstone National Park.

Prokaryotes usually live as single cells or in simple strings or clusters. Although most people think of germs and diseases when they hear the word “bacteria,” most bacteria benefit other living organisms. For example, helpful bacteria that live on your skin crowd out harmful bacteria that also like to live on your skin. Bacteria that live in your intestines help you digest your food. Bacteria at treatment plants help clean wastewater from bathrooms and kitchens. Bacteria that live in the soil break down organic and inorganic materials so they can be reused by plants and animals.

The various prokaryotic cells share similar features, illustrated in Figure 2.23. A cell wall, outside the cell membrane, serves as a covering that supports, shapes, and protects the cell. The capsule, a gel-like coating outside the cell wall, adds additional protection. Some bacteria have long, very thin attachments called *flagella*. These rotate like propellers so the bacterium can move around in a fluid. Other bacteria have many short, hair-like bristles called *fimbriae*. These help them to attach to surfaces. Prokaryotes have a single twisted-up loop of DNA in the region of the cytoplasm called the *nucleoid*. The cytoplasm also holds small additional rings of DNA called *plasmids* and thousands of ribosomes for making proteins. Photosynthetic *cyanobacteria* have thylakoids (discussed below) filled with light-absorbing pigments in their cytoplasm.

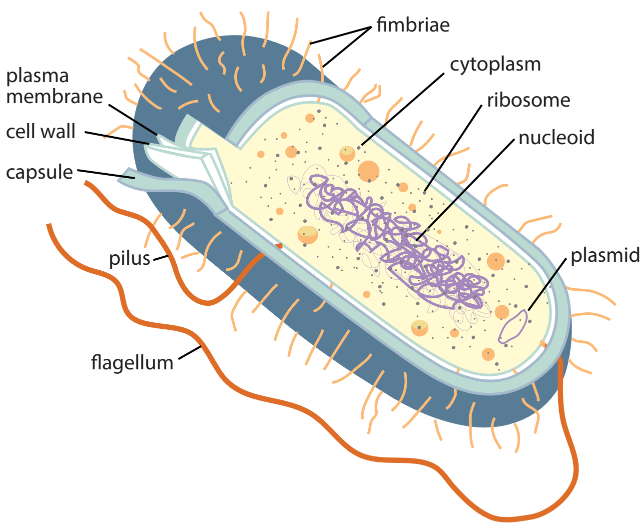


Figure 2.23. A prokaryotic cell.

Members of the Eukarya domain have cells that each contain a membrane-bound nucleus. The nucleus separates the DNA, which is wound up into structures called *chromosomes*, from the cytoplasm of the cell. Protists (mostly single-celled microscopic organisms), plants, animals, and fungi are all members of this domain. Figure

2.24 illustrates the basic structure of a eukaryotic animal cell.

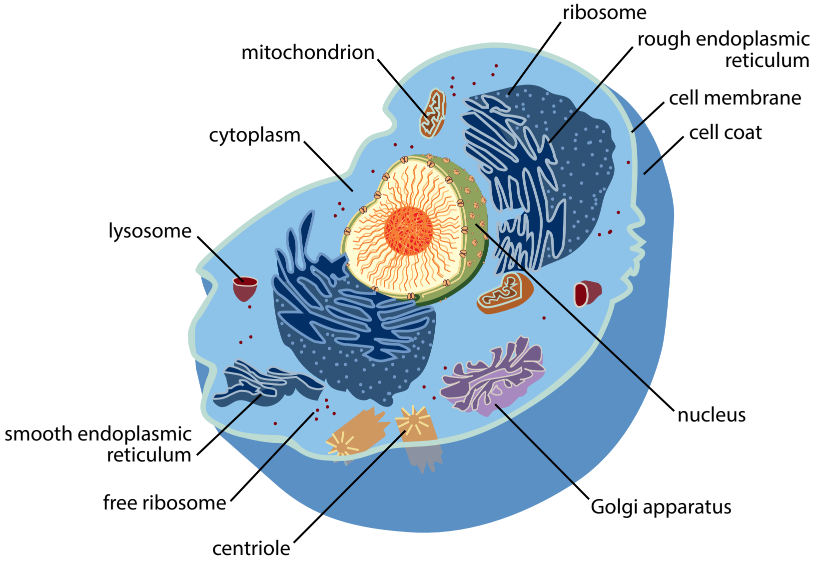


Figure 2.24. A eukaryotic animal cell.

In addition to a membrane-bound nucleus, eukaryotic cells have many other membrane-bound *organelles*, small membrane-bound structures that perform services for the cell. These are described below. All the organelles in a cell work at the same time. The cells take in chemicals and the organelles process them. Ribosomes, the large molecules that make proteins from amino acids, are scattered throughout the cytoplasm and also attached to the rough endoplasmic reticulum (ER). The ER is a complicated system of channels and tiny sacks attached to the outer membrane of the nuclear envelope. Rough ER is studded with ribosomes that make proteins. Smooth ER makes other substances, such as lipids that store energy.

Once proteins and other cell products have been made, they must be sorted and packaged for delivery to places both inside and outside the cell. This job is carried out by cell organelles called the *Golgi apparatus*. The Golgi apparatus is a set of stacked, flattened membranes that put proteins and other cell products into membrane-bound structures called *vesicles*. The vesicles deliver the cell products to areas inside the cell and to the cell membrane for release outside the cell.

Just as the 24-hour bagel shop stores food and ingredients in refrigerators and cabinets, cells store water, waste, food, and other cell products in membrane-bound organelles called *vacuoles*. Plant cells, such as the one illustrated in Figure 2.25, typically have large vacuoles that take up much of the space inside each cell. When it is time to break down and recycle wastes, an organelle called a *lysosome* releases digestive chemicals into the vacuole. While the cell is healthy, digestive chemicals are placed into vacuoles only when needed. When the cell dies, the lysosome's membrane disintegrates, and digestive chemicals are released to break down the cell's contents.

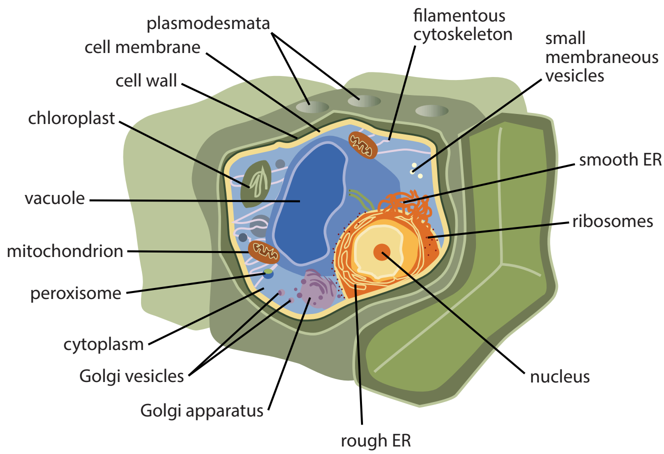


Figure 2.25. A eukaryotic plant cell.

2.4.4 Cell Wall

Just as the 24-hour bagel shop resides within the walls of a building, some types of cells are protected by *cell walls*. Plants, algae, fungi, and most bacteria have tough, rigid outer coverings that protect the cell and give it shape. A plant cell wall is made of the carbohydrate cellulose. The long, threadlike fibers of cellulose form a thick lattice that lets water and materials pass through. As illustrated in Figure 2.26, cell walls may also contain pectin, the compound used to thicken jams and jellies, and lignin, a compound that makes the walls stiff.

2.4.5 Cell Membrane

As previously mentioned, all cells are enclosed in a cell membrane made of a bilayer of phospholipid molecules studded with protein molecules. This flexible membrane serves as a boundary that separates the contents of the cell from the immediate environment. In cells that have a cell wall, the cell membrane is inside the wall. The cell membrane controls which molecules enter and leave the cell.

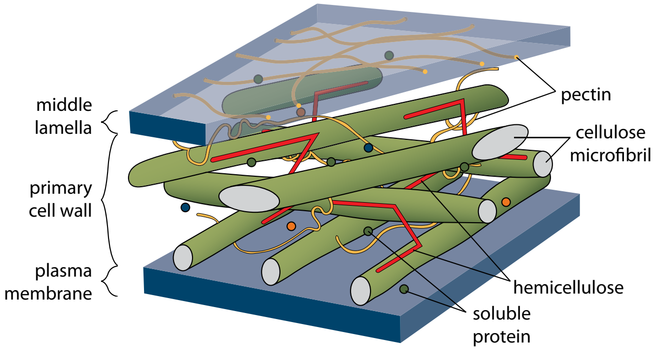


Figure 2.26. A plant cell wall.

Small molecules, such as water, move freely through the cell membrane, but larger molecules must be transported with the help of protein molecules embedded in the cell membrane. Figure 2.27 illustrates some protein molecules within a cell membrane. Some protein molecules act as pumps that move sodium, potassium, calcium, and hydrogen into or out of the cell, keeping the interior in the right balance. Some proteins work like gates, letting some molecules into the cell and others out of the cell. Other proteins work like portals, letting substances pass from one cell into another. Protein receptors give the cell information about the outside environment or detect hormones (chemical messengers). Hormones tell the cell to perform specific tasks. Another kind of protein within the cell membrane acts like a sign that identifies the type of cell to other cells.

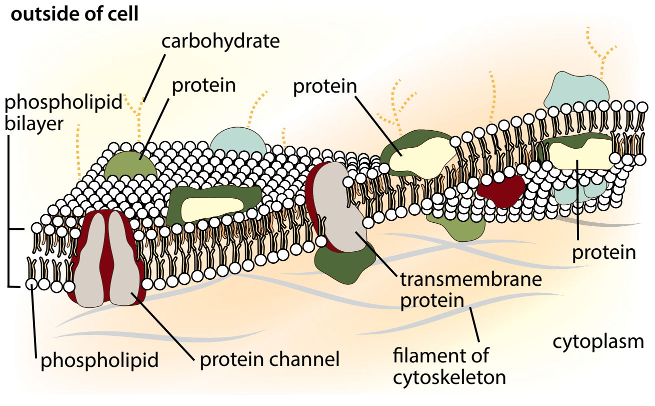


Figure 2.27. The cell membrane.

2.4.6 Cytoplasm

The cell membrane encloses cytoplasm, a jelly-like fluid made up of water, salts, and dissolved organic molecules, such as proteins, lipids, and carbohydrates. Like the coffee beans, syrups, and baking ingredients in the 24-hour bagel shop, these organic molecules are the raw materials used by the cell to make cell structures or to send out of the cell for use elsewhere in the organism. The cytoplasm provides the right environment for the many chemical reactions needed to produce energy, convert organic molecules into needed proteins, or break down old proteins to be recycled. These reactions take place both in the cytoplasm and, in eukaryotic cells, within many organelles, or "little organs," that fill the cytoplasm.

2.4.7 Cytoskeleton

The cell is not just a jelly-filled, shapeless bag. It maintains its shape with a *cytoskeleton*, an internal skeleton made of a network of fibers. Thin, hollow tubes of protein and thin, solid protein fibers arranged in a complex framework hold the organelles of the cell in place. The fiber network also provides a system of "tracks" that motor proteins use to move cell products from place to place inside the cell or to the cell membrane. Another use of the cytoskeleton is exhibited by the amoeba, a type of single-celled organism shown in Figure 2.28. The amoeba uses the cytoskeleton to push out the cell membrane, forming a *pseudopod*, or "false foot," to pull itself along.

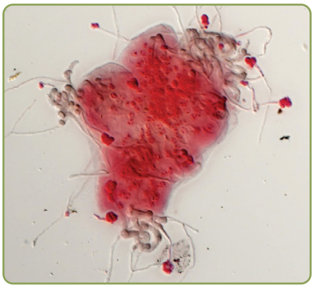


Figure 2.28. An amoeba. There are many different types of amoebas, but they are all eukaryotes.

2.4.8 Nucleus

Like the manager who directs the daily operations of our 24-hour bagel shop, giving information to the chefs, baristas, and delivery staff, the *nucleus* of a eukaryotic cell directs the cell's activities. The nucleus, illustrated in Figure 2.29, is protected by a *nuclear envelope*, a membrane that is like the cell membrane but made up of two layers with a narrow, water-filled space between. Materials can enter and exit the nucleus through nuclear pores—small openings in the membrane. The nucleus stores DNA, the organic molecules that determine the physical characteristics of an organism. Like the recipes used by a chef, DNA molecules provide the information the cell needs to build proteins as they are needed. Every cell in an individual contains the same DNA, but in each cell type certain instructions are used and others are not. The proteins made by a cell determine the cell's structure and the functions the cell can perform. Cells in different parts of an organism perform different functions. For example, muscle cells are designed to contract, nerve cells are designed to control body activities, skin cells are designed to cover and protect, and red blood cells are designed to deliver oxygen. The instructions carried in the DNA make up the hereditary information that organisms pass on to the next generation in order for the species to survive.

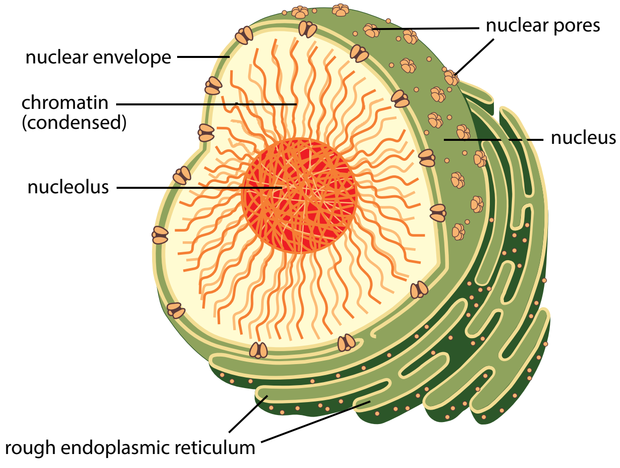


Figure 2.29. The cellular nucleus.

2.4.9 Chloroplasts

All organisms must have a steady supply of energy to maintain life and grow. Cells within an organism use energy to process food, make new proteins, get rid of waste, and communicate with each other. The source of that energy is food. A falcon, for instance, might get energy by eating a mouse. Energy flows from the mouse to the falcon. The mouse gets its energy by eating a grasshopper. Energy flows from the grasshopper to the mouse. The grasshopper gets its energy by eating grass. Energy flows from the grass to the grasshopper. All organisms that devour other organisms are called *consumers*. But grass doesn't eat, so how does grass get energy?

All organisms that devour other organisms are called consumers. Organisms such as plants that make their own food called producers.

Plants use the energy in sunlight to make food within their cells. Because plants make their own food, instead of eating other organisms for energy, they are called *producers*. Producers use the energy in sunlight to join together carbon dioxide and water, making carbohydrates and releasing oxygen. A simplified chemical equation for this process can be written as follows:

solar energy + carbon dioxide + water → carbohydrate + oxygen

Plants can make carbohydrates because they have oval-shaped organelles called *chloroplasts* within the cytoplasm of their cells. Chloroplasts, illustrated in Figure 2.30, absorb light energy and convert it to chemical energy for the manufacture of food in the process called *photosynthesis*. Like the nucleus, this organelle is surrounded by a double-membrane and it contains its own DNA. Chloroplasts hold hundreds of *thylakoids*, flattened compartments connected by narrow tubes. These compartments contain the green pigment *chlorophyll,* giving leaves and stems their green color. Chlorophyll absorbs blue, violet, and red light and the chloroplasts use that light energy to make food. Chloroplasts can move around inside a cell, responding to light intensity and direction. The carbohydrates they produce might be stored in other parts of the plant, or they might be broken down by the cell's mitochondria to produce energy in the form that the cell uses.

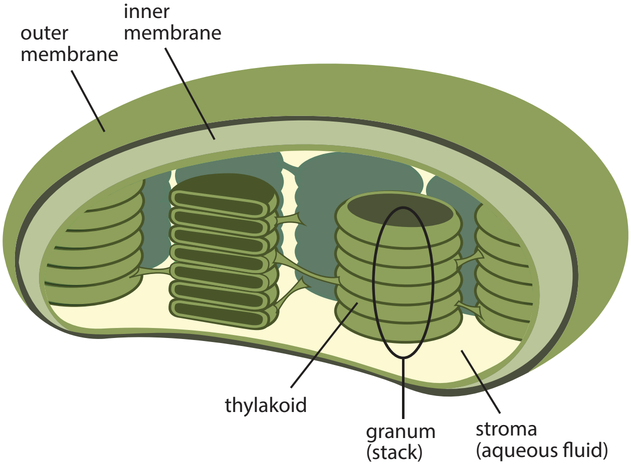


Figure 2.30. A chloroplast.

2.4.10 Mitochondria

Just as a gas or electric company provides energy to the 24-hour bagel shop to power the ovens, coffee makers, refrigerators, dishwashers, and lights, the *mitochondria* (singular: mitochondrion) within a cell provide energy for all the energy-requiring processes of the cell. For this reason, the mitochondria are sometimes called the "powerhouses of the cell."

Mitochondria are the powerhouses of the cell.

All eukaryotic cells, including those of plants and algae, contain mitochondria. Plants have both mitochondria and chloroplasts. Chloroplasts make food and mitochondria break down that food to form molecules of ATP, a chemical that acts as the common energy carrier in cells.

Let's Talk About Cell Biologist Yoshinori Ohsumi

Scientists have recognized for some time that cells break down waste products. But not realizing the importance of this process, no one had spent much time or thought on research until a cell biologist named Dr. Yoshinori Ohsumi led the way into this new field of study.

In the 1990s, Dr. Ohsumi conducted experiments with baker's yeast to identify genes that control how cells destroy their own contents.

Dr. Ohsumi, shown in the figure, was born in Fukuoka, Japan, in 1945. He received a Ph.D. from the University of Tokyo in 1974 and began working in the field of chemistry. He soon switched to molecular biology and was employed as a junior professor at the University of Tokyo. He began with studies of the duplication of DNA in baker's yeast, but his skill with the microscope led him to start investigating yeast vacuoles in 1988. He examined the process by which damaged cell proteins and organelles are broken down and recycled.

The process that cells use to break down their parts is called *autophagy*, a Greek term meaning "self-eating." Starving cells digest and recycle proteins and nonessential components to reuse for energy. Cells can rid themselves of damaged proteins and organelles and clear out debris. Autophagy is also used to destroy viruses and bacteria within the cell.

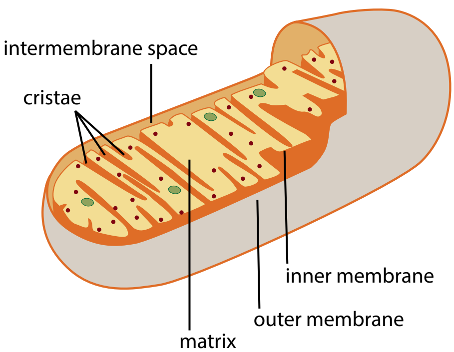
Scientists had previously understood that autophagy was how cells got rid of waste, but they did not realize the importance of the process for prevention of disease. The autophagy genes and metabolic pathways that Dr. Ohsumi discovered in yeast are also used by higher organisms, including humans. The process of autophagy is vital for cells to survive and to stay healthy. If cells fail to clear out waste adequately, the cell damage can play a part in aging, cancer, infectious diseases, immunological diseases, and neurodegenerative disorders. Dr. Ohsumi's work opened a new field of scientific study. Now, hundreds of researchers around the world are working in this new area. One researcher, Beth Levine, reported in 1999 that a mammalian autophagy gene could suppress tumor growth. Other researchers are learning more about the part that autophagy plays in cancer, Parkinson's disease, Type 2 diabetes, and other disorders.

Dr. Ohsumi earned the 2016 Nobel Prize for Physiology or Medicine for his pioneering work on how cells recycle. He was 43 years old when he made the discoveries that the Nobel Assembly recognized. Dr. Ohsumi is described as a quietly daring man and a very humble yeast geneticist. He says, "I like to tell young people that not all can be successful in science, but it's important to rise to the challenge."

The process of converting food into energy is the reverse of photosynthesis:

carbohydrates + oxygen → carbon dioxide + water + energy (molecules of ATP)

Mitochondria are rod-shaped organelles with an outer and an inner membrane, illustrated in Figure 2.31. The space between the outer and inner membranes is called the *intermembrane space*. The smooth outer membrane is covered with pores that allow molecules to pass through. The inner membrane is shaped in folds called *cristae* and covered with transport proteins, ion pumps, and ATP generators. These protein molecules serve the same purpose as those embedded in the cell membrane. They select which molecules enter or leave the inner space within a mitochondrion. This inner fluid-filled space is called the *matrix*.



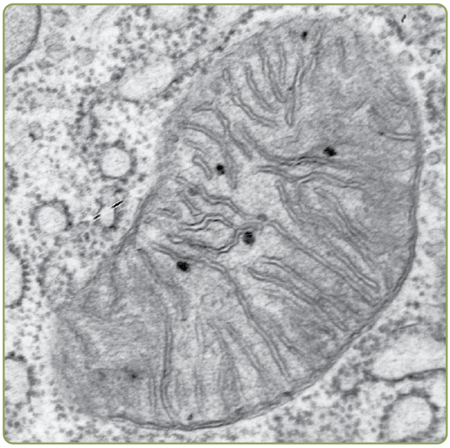


Figure 2.31. A mitochondrion.

The series of folds of the inner membrane layer provide a large surface area for the chemical reactions that break down carbohydrates and fats and produce ATP molecules. This complex process is called *cellular respiration*. The fluid-filled matrix contains DNA, ribosomes, and enzymes that participate in the chemical reactions. The oxygen needed for this process comes to the cell through the blood stream. Generating the energy in the ATP also produces heat that organisms use to maintain their body temperature.

Despite the simple cell models you see in pictures such as Figure 2.24, most mammal cells contain between 1,000 and 2,000 mitochondria! Cells that need more energy, such as heart muscle cells, have more mitochondria than other cells.

2.4.11 Ribosomes

Ribosomes are large molecules made of protein and RNA. They have two sections that fit together like a clamshell with a slot in between. Like the chefs that make the bagels in the 24-hour bagel shop, ribosomes make proteins from amino acids. Just as a chef follows a recipe, the ribosomes follow the instructions that come from the DNA in the nucleus of the cell. These instructions specify the molecules (amino acids) needed to make specific proteins and the order in which they must be put together.

Learning Check 2.4

1. Why is the cell considered to be a living structure?
2. Compare and contrast prokaryotic cells and eukaryotic cells.
3. Compare and contrast eukaryotic plant cells and eukaryotic animal cells.
4. How does the size of a bacterial cell compare to the size of an average animal cell?
5. If a single cell can carry out all the functions necessary for life, why are larger plants and animals made up of trillions of specialized cells rather than one large cell?
6. What types of cells are protected by cell walls?
7. Describe the structure and purpose of each of the following:
    a. cell wall
    b. cell membrane
    c. cytoplasm
    d. nucleus
    e. chloroplasts
    f. mitochondria
    g. ribosomes

Chapter 2 Exercises

Answer each of the questions below as completely as you can. Write your responses in complete sentences.

1. How does the size of a bacterium compare with the diameter of a single human hair?
2. Identify and describe three states of matter.
3. Describe the particles found in an atom.
4. List the six elements that are most important in living things.
5. Identify the significance of seven remarkable properties of water.
6. Describe the importance of organic molecules.
7. What does the cell theory state?
8. What evidence supports the cell theory?
9. How is a cell like a 24-hour bagel shop?