What could a sample of your DNA reveal about you?

How might the use of this technology affect your life?

A thousand years ago, ideas about health and nature were characterized by tradition and magic, not by skepticism and experimentation. For example, many people believed that disease was the result of evil forces. Illness often was attributed to “bad blood,” not germs, and bleeding a person was a common therapy. The cells and molecules that cause disease were unknown. Similarly, the effects of environmental changes on the living world were not well understood.

Science provides a structure for studying the world in a way that explains natural phenomena. Unlike beliefs about evil forces, scientific explanations can be tested. The answers to complex questions are not obvious, but we have made dramatic progress. When your grandparents were in high school, the structure of DNA was unknown. Your parents went to school when animal cloning was still science fiction. Now, genetically modified organisms manufacture drugs, and the complete genetic sequences of many organisms are known. What will the science of the third millennium be like?

This chapter introduces biology, the study of life. Biology unites scientific methods with technology to search for answers to fundamental questions about the living world.
The New Biology

P.1 Biology in Your World

Many scholars believe that biology will be the most influential science of the 21st century. When you consider the prevalence of biology in the news, that prediction seems reasonable. Nearly every day there is a story about medicine or disease, genetic engineering, nutrition, or environmental pollution (Figure P.1). There also are many topics that affect your life every day. How do antibiotics work? Does a family history of cancer guarantee that you will get cancer? How much do genes affect your behavior? What is cloning?

Answers to these and similar questions lie at the levels of cells and molecules. Understanding the molecular basis of life is the focus of this book. Instead of simply describing whole organisms (living things), you will learn how genes, molecules, and cells make organisms function. For example, scientists now understand the functions of many of the genes in viruses. That knowledge is helping medical researchers design new vaccines.

The biology of the new millennium will confront you with questions and choices that your parents never imagined. Should a person’s genetic sequence be available to insurance companies? Is it ethical to engineer cells genetically that can be passed to future generations? Who will resolve the social issues that stem from new technologies? Without an understanding of how living systems function and how they are interrelated, it is impossible to make intelligent decisions about issues that affect your life and the lives of those around you. This book will help you acquire a basic knowledge of biology, which, in turn, will enable you to understand biological issues and to make informed judgments in the future.

FIGURE P.1
Biology in daily life. Examples include new techniques for the care of premature infants (a), the benefits of staying in shape (b), and the hazards of water pollution (c).
P.2 A Biological View of AIDS

AIDS (acquired immune deficiency syndrome) is an example of how biology can shed light on problems of global importance. AIDS is caused by a virus that infects a type of cell in the immune system, which normally helps fight infection. As the virus destroys these cells, the immune response gradually is destroyed as well. Infections that would be minor in a healthy person can be fatal in a person with AIDS. Because an immune system weakened by the virus provides the opportunity for these infections, they are called “opportunistic infections.”

The virus responsible for AIDS was identified in 1983 and later named human immunodeficiency virus, or HIV (Figure P.2). Although HIV is a major concern of health officials in the United States, more than 95% of all HIV-infected people live in developing countries.

The genetic material of the virus is copied inside infected cells and then becomes part of the cells’ own genetic material. As a result, infected cells lose their ability to function normally and become “factories,” producing more HIV. Each infected cell releases many new viruses, each capable of infecting other cells. Infected cells also may merge with nearby uninfected cells to form a large mass. This mode of spreading between cells worries researchers, because it means that drugs or vaccines that cannot enter the cells themselves will not prevent the spread of infection.

Because HIV affects the body at the cellular and molecular levels, biologists use their knowledge of the functions of molecules and cells within the immune system to develop treatments for AIDS. One of the first drugs used to treat people with AIDS was AZT. AZT interferes with the reproduction of HIV. Today, physicians prescribe a combination of drugs that interrupt different processes involved in HIV infection. Combination therapy is more effective at keeping infection under control than AZT alone. Interestingly, some people who have been repeatedly exposed to HIV never become infected. Scientists are studying a gene that appears to protect those individuals. Despite these advances, many HIV-infected individuals eventually develop an infection that physicians cannot treat, and they die. To date, an estimated 25 million people worldwide have died from the AIDS epidemic and another 40 million people are infected with the virus.

Because treating infection is so difficult, many biologists are focusing, instead, on developing a vaccine that would prevent infection. One approach to vaccine development uses genetic engineering to insert parts of the genetic material from HIV into the genetic material of harmless viruses. The modified virus might then be injected into the body, triggering an immune reaction against the HIV proteins. Then, if the vaccinated individual is exposed to HIV, the immune system should recognize the virus and destroy it before it can cause harm.

The genetic material of HIV mutates, or changes, rapidly. Therefore, a vaccine that is effective against one strain, or form, of HIV may not be effective against another strain. The virus evolves so rapidly that different strains develop within the course of infection in a person. Today, after testing more than 15 different vaccines, scientists have not yet discovered one that is safe and effective. Scientists hope, however, that a better
understanding of the molecular basis of infection will lead to a protective vaccine. Until then, avoiding exposure to the virus through protective behavior is the most effective way to avoid becoming infected.

**P.3 Growth Hormone: New Solution, New Problem**

What do you consider “short” (Figure P.3)? Is a person short if he is 5 feet 2 inches (about 157 cm) tall? If she is 5 feet 2 inches tall? Ideas about “normal” height vary widely. If there were a way to make each of us as tall as we wanted to be, would that be a wise or foolish use of biological knowledge?

Treatment is now available for a disorder called growth hormone deficiency. Human growth hormone (GH), a protein that helps to control growth, is made by a small gland in the brain called the pituitary. Most people produce enough growth hormone to attain a “normal” height. Children with growth hormone deficiency, however, do not produce enough GH. They cannot reach a height in the normal range unless they are given extra hormone. However, GH treatment does not increase the final adult height of all children who are short as a result of heredity. The search for a solution to growth hormone deficiency must begin at the level of molecules because the deficiency involves the interaction of molecules in cells.

In the past, children with the deficiency were treated with GH isolates from the brains of people who had died. Many pituitary glands were needed to obtain even small amounts of GH; therefore, the procedure was expensive. More recently, this procedure was found to be dangerous. Some of the pituitary glands contained a deadly pathogen that was transmitted to the children along with the hormone.

Genetic engineering now enables biologists to use bacteria to produce GH. Human DNA, the genetic material, is inserted into bacteria. The bacteria then can manufacture human GH. GH produced by bacteria is good news for children with growth hormone deficiency, but it has raised some troubling questions. For example, should GH be prescribed for normal teenagers who merely wish to add a few inches of height to gain an advantage in athletics? GH can have some serious side effects. If doctors do not make the hormone available, will aspiring athletes obtain it illegally and use it without supervision?

The dilemma of how to use GH is an example of the issues raised by new technologies. The fact that all organisms share the same genetic material—DNA—has led to startling breakthroughs for health and medicine. New technologies may improve our ability to fight disease, solve environmental problems, and increase life expectancy; but they also create new, often difficult choices for society.
Biology, Ethics, and Public Policy

An improved understanding of biology and an ability to manipulate some basic life processes raise many new and troubling issues. For example, medical technology can save many severely handicapped infants who might have died had they been born only 15 years ago. Should attempts be made to save such babies? Should fetuses found to have a genetic disorder or a birth defect be aborted? On whom shall we test new vaccines against AIDS, especially if some small risk exists that the vaccine will cause AIDS? Technology now allows us to identify and test for certain genes that cause disease. Is it beneficial to patients to diagnose a condition for which there is no known treatment? (See Figure P.4.)

These issues involve a mixture of science and ethics—the study of right and wrong actions. Many universities now train people in bioethics, the application of ethics to biological issues. Bioethicists work in hospitals and research institutions.

Science can be very helpful in telling us what we can do and in predicting the effects of each alternative. Science, however, cannot tell us what we should do. Although evidence might point toward one alternative, the final decision often is a matter of values. Those values are represented in public policy—laws and regulations that govern how science is applied.

Public policy should be based on sound ethical judgments, but that is not always enough to make policies workable. A policy may be ethically sound, but if most people do not agree with it or if it cannot be enforced, it probably will not work. Many of the issues in this book are so new that there are no national policies to govern them, and there still is sharp ethical disagreement about many of them. Each person has a responsibility to understand and contribute to debates about the ethical and policy aspects of advances in science and technology. The first step is understanding the science involved. This book will help you do that. The second step is to analyze bioethical issues. Investigation PA is a model that will help with the second step.

FIGURE P.4
Young people with unknown risks of developing cancer. Several genes appear to be involved in inherited forms of breast cancer. Once a test to identify carriers is available, should these young women be tested, even though there is no cure for breast cancer yet?
Everyone makes decisions every day. Most of the decisions people make are based on what they feel will be the best solution. Feelings and judgments of how others feel play a major role in how you choose to resolve your day-to-day problems. Effective problem solving, however, goes beyond feelings. To solve a problem, you must also combine what you already know with new observations. Then, based on your knowledge of the situation, you can evaluate the problem and formulate the best plan to solve it.

Imagine that it’s the weekend and you are to meet your friends at the movies at noon. Suddenly you notice it’s 11:45. You race to get ready and then jump in the car. What route is the fastest? You choose the best route based on what you know about the distance, the amount of traffic on the roads at that time, and the number of stoplights you are likely to encounter. If a lot of other drivers are using the same route, it might be faster to use an alternative route. In essence, you make observations and combine those observations with your best guesses to arrive at a possible solution. If you are late, next time you may try another route. Eventually, through trial and error, you find the fastest route.

In science, problem solving is based on the interpretation of data, which is information gained through observation. For example, you could time every possible route to the theater twice—once in heavy traffic, and once with light traffic. After several more trials, you could then interpret the results. If one route was consistently faster than others, you would have solved the problem by using scientific methods.

Solving problems with scientific methods can help you determine what is reasonable and what is not. It can help you evaluate claims made by others about products or events. It can help explain how organisms function and how they interact in the environment.

The easiest way for you to become familiar with these methods is to use them yourself (as you frequently will in this course) and to see how other people use them. One good example of scientific problem solving involves the topic of evolution. Evolution is one of the major unifying themes of science as inquiry—the understanding that all is not known and that concepts must be revised and restructured as new data become available—pervades all scientific methods.
biology. How widely does evolution apply, and how does it occur? What data provide evidence of evolution? In the following sections, you will see how scientific methods were used to develop a theory that explains how organisms change through time.

P.5 A Mechanism for Evolution: Science at Work

The world is filled with beautiful and intriguing organisms. It also contains a fossil record of equally amazing extinct forms of life. Observe the pictures of organisms in Figure P.5. Which organisms are similar and in what ways? Which organisms are different and in what ways? More important, how did these diverse forms arise?

By the beginning of the nineteenth century, biologists had observed that living organisms were different from the fossil organisms found in rocks. These observers developed a theory—evolution—that the organisms of the past had given rise to the organisms of the present, and that organisms had changed through time. A theory explains current observations and predicts new observations—in this case, observations about how organisms change through time. The theory of evolution, for example, predicts that there should be observable differences between modern organisms and fossils found in rocks, as well as observable similarities. Evidence from thousands
of observations of modern and fossilized organisms from all over the world supports the theory of evolution. (For more on theories, see “Theory in Science” in Section P.6.)

How does evolution occur? A French biologist, Jean Baptiste Lamarck (1744–1829), was one of the first to propose that organisms change through time. He proposed that a change in the environment produces a need for change in animals. Thus, if an animal needs to use one part of its body frequently, that part will become stronger and more well-developed. Conversely, if an animal uses some part of its body infrequently, that part will slowly weaken, become smaller, and may disappear. Lamarck assumed that these acquired characteristics would be passed on to the offspring in that changed form.

As with other scientific ideas, Lamarck’s ideas could be evaluated through a series of hypotheses—explanations that are testable through experimentation or observation. One hypothesis based on the theory of evolution could be stated as follows: Ancient organisms have given rise to modern organisms by evolution.

Predictions that follow from hypotheses can be stated in an If . . . then format. One prediction based on Lamarck’s explanation of evolution through inheritance of acquired characteristics could be stated as follows: If a male and a female increase the size of their muscles through weight training, then their children will be born with large muscles. We know from observations that this is not the case. Therefore, the hypothesis must be rejected.

Lamarck’s explanation does not do a very good job of predicting observations about the changes of organisms through time. Extensive experimentation for more than 100 years has failed to show that acquired characteristics are inherited.

The British naturalist Charles Darwin, who lived from 1809 to 1882, developed a theory of evolution that scientists still use. Many things influenced Darwin during his life. One was his experience as a naturalist on the five-year voyage of the Beagle (Figure P.6) during which he observed

**FIGURE P.6**

*Darwin and the route of his exploration.* Young Charles Darwin (a) sailed around the world on the *Beagle*. The route taken (b) included stops in South America and the Galápagos Islands. During the trip, Darwin found evidence that would later support the theory of evolution by natural selection.
unique and diverse organisms from around the world. Another influence was a book written by Darwin's friend, the geologist Charles Lyell (1797–1875). Lyell promoted a hypothesis, first developed by a Scot, James Hutton, that natural forces existing in the past were the same as those that exist today. This view, called uniformitarianism, maintains that geological forces produced changes on Earth in the past, and it predicts that those same forces will continue to produce changes in the future.

Darwin raised the following questions: If Earth has had a long history of change, what was it like before now? Could it have supported the diversity of life it has now? What other forms of life might have lived before now? Darwin reviewed existing data and made numerous observations around the world as he formulated his answers to these questions.

P.6 The Theory of Natural Selection

On the basis of his extensive research, Darwin published a book in 1859 titled The Origin of Species. Darwin's theory stated that new forms of life are produced by means of natural selection, the survival and reproduction of organisms that are best suited to their environment (Figure P.7). Natural selection occurs because some members of a population or species have physical or behavioral characteristics that enable them to survive and to produce more offspring than others. (A species is a group of similar organisms that naturally reproduce with one another—see Figure P.8.)

**ETYMOLOGY**

uni- = one (Latin)
formis = form (Latin)
Forces in the past and present were uniform.
Because offspring tend to inherit the characteristics of their parents, certain characteristics become more common in succeeding generations. Characteristics that increase the chances that an organism will survive and reproduce in its particular environment are called adaptations. Darwin based his theory on several major observations, including the work of other scholars such as the economist Thomas Malthus. Malthus proposed that the number of organisms in any species or population tends to increase from generation to generation in a geometric progression, whereas the food supply increases in an arithmetic progression (Figure P.9). If humans, for example, continued to reproduce at the same rate, they would eventually outstrip the food supply.

Malthus’s writings provided Darwin with an important idea: Not all organisms live long enough to reproduce because of limited resources, such as food, water, and other environmental factors. This difference in survival among members of populations has kept those populations in check. Darwin realized that competition for survival could be a powerful force in the evolution of species. Some organisms survive this competition; others do not.

Darwin also observed that naturally occurring variations, or small differences (Figure P.10), occur within populations. On the Galápagos Islands, which Darwin visited during his travels, some members of the same finch species have short, thick beaks while others have longer, thinner beaks. On the basis of these observations, Darwin concluded that some variations would help members of a species survive in a particular
environment (Figure P.11), whereas other variations would not be helpful. His theory proposes that natural selection tends to eliminate those organisms with variations that are not advantageous. For example, scientists have observed that during drought Galápagos finches with long, thin beaks tend to be at a disadvantage because they cannot crack the tough seeds that are plentiful under those conditions.

![Population of ladybird beetles](image1.png)

**FIGURE P.10**
A population of ladybird beetles, ×2. How many differences can you see within this population? What is the range in number of spots present? What important characteristic of populations does this illustrate? What is responsible for these differences?

![Variation aids adaptation](image2.png)

**FIGURE P.11**
A variation that aids adaptation. Notice the shape of the beak on this finch. Under what environmental conditions might a long, thin beak be advantageous?
Darwin’s theory suggests a number of predictions. For example, if organisms with favorable variations are most likely to survive and reproduce, then those organisms with unfavorable variations would be less successful at reproduction and would, therefore, die out. Because variations can be inherited, the favorable variations—adaptations—would accumulate through time. Further, if organisms with those favorable variations become so different from members of the original species that they can no longer reproduce together, then a new species may have evolved (Figure P.12).

Extensive fieldwork and experimentation have supported Darwin’s theory of natural selection as a mechanism for evolution. For example, scientists studying fossils predicted that they would find fossils that represented intermediate forms between living organisms and fossils discovered in the older layers of Earth. This prediction has been confirmed in an overwhelming number of cases by scientists all over the world who have discovered fossils of organisms such as birdlike reptiles and dog-sized horses.

Lamarck and Darwin proposed different theories to explain the same observation: Organisms change through time. Darwin’s theory of evolution by natural selection has prevailed because it explains existing observations and predicts future observations.

The theory also explains the similarities between humans and other animals, which has some practical consequences. For example, animals such as rats and monkeys share certain features with other animals, including humans. Thus, medical scientists can often apply what they learn from lab animals to humans.
Theory in Science

What do most people mean when they say they have a theory about something? Perhaps you have a theory about why the football team lost its first game. When scientists use the word *theory*, they do not mean guess or idea. Instead, a theory is a comprehensive explanation of facts, laws, and reasoning that is supported by many observations and multiple lines of evidence. Theories are accepted by the scientific community.

Theories are important in science because they help organize vast numbers of facts and observations generated by experimentation. In the case of evolution, Darwin built a framework for explaining the relationships that he, and many naturalists before him, observed among living and extinct organisms. Descent with modification and natural selection are two theories encompassed by the broader theory of evolution, a phrase that Darwin did not use.

Because theories lead to logical hypotheses, they allow scientists to make and test predictions. This is an important feature of science. Darwin's theory of *descent with modification*, which means that related organisms share a common ancestor, allows predictions that can be tested. For example, chimpanzees and gorillas share a great number of physical characteristics, but they also show some differences. Descent with modification predicts that the greater the similarity between two groups of organisms, the closer is their relationship. An examination of the DNA of chimps and gorillas suggests that both evolved from a common ancestor that lived about 12 million years ago. Chimps and baboons, which share fewer characteristics, are less closely related. DNA evidence suggests a common ancestor about 25 million years ago (see figure to the right).

The theory of natural selection leads to the prediction that changes in a species’ environment will tend to favor organisms with certain characteristics or adaptations. For example, around 1900, a biologist named H. L. Bolley used natural selection to predict changes in the characteristics of flax plants. He reasoned that, if he collected seeds from the occasional flax plants that did not die in the presence of a certain fungus, then he could mate those plants and eventually produce a population of flax plants resistant to the fungus. Bolley was correct, and the flax farmers benefited from his application of the theory of evolution.

Theories such as evolution theory, atomic theory, and the germ theory of disease have been supported repeatedly by data resulting from hypotheses. In addition, virtually no opposing data have yet been found, further strengthening these theories. Any theory, however, can be changed or even discarded if new experiments and observations do not support the model. All theories mentioned here have been modified as new research has been done. And undoubtedly these theories will be modified in the future. This continuous modification is another example of the way science works.
Science as a Way of Knowing

P.7 Scientific Perspectives

There are many ways to explain natural phenomena. For example, history, religion, art, philosophy, and sociology all provide ways for people to examine the world. In addition, they all contribute to today’s body of knowledge.

Science is one way of explaining the natural world. Several characteristics generally define science.

1. Science is based on the assumption that the natural world can be investigated and explained in terms we can understand.
2. Science is based on the results of observations and controlled experiments.
3. The results of these observations and experiments must be (at least in principle) repeatable and verifiable by other scientists.
4. The findings of science must be refutable. In other words, if a hypothesis is not supported by evidence and observations, then the hypothesis must be rejected or modified. The same principle holds true for theories.

Methods of explaining natural phenomena that do not share these characteristics do not qualify as science.

Nonscientific ways of explaining natural phenomena are valuable as well, but they should not be confused with science. For example, poetry conveys metaphorical messages that can be quite powerful, and the exact meaning of a poet’s words must be interpreted by each individual. Science, on the other hand, is more literal. In science, words are chosen to convey as precise and clear a meaning as possible.

Science is a human enterprise, so it can be influenced in some ways by personal biases and by politics. Consider the great astronomers Copernicus and Galileo. Copernicus (Figure P.13a) developed a theory that Earth is one
of several planets orbiting around the Sun. Galileo (Figure P.13b) observed moons orbiting around the planet Jupiter. Their conclusions challenged the authority of the church, which interpreted the Scriptures at that time to say that the Sun moved around Earth, which was the center of the universe. Both scientists were chastised by the church. Galileo was forced to sign and publish a statement saying that his work was incorrect, and he was then sentenced to permanent house arrest.

No matter what Galileo signed, it did not change the fact that Earth is not the center of the solar system. Rejecting science does not change the science—it merely prevents people from learning and understanding what it says.

P.8 Your Role as a Biologist

Science is a method of answering questions and explaining natural phenomena. You have already encountered a few of the many questions biologists ask when they study living things. Throughout this course, you will be asked to answer such questions as, To what environment is this organism adapted? What is being released into my environment that could be hazardous to my health? How does a change in DNA affect the proteins of an organism?
**Focus On**

**Pseudoscience**

**Pseudoscience** means, literally, false science. Some investigators claim their research is scientific, but it does not meet the definition of science. Such work can be classified as pseudoscience. Some examples of pseudoscience include astrology, “miracle cures” for diseases such as cancer and arthritis, homeopathy, and some dieting programs and health practices. A great deal of time, effort, and money can be saved by learning to evaluate pseudoscientific claims carefully (Figure P.14). The following example shows the consequences of confusing science and pseudoscience.

In the 1980s, the states of Arkansas and Louisiana enacted laws requiring science teachers to devote equal time in class to teaching evolution and creationism, or “creation science.” The writers of the Arkansas law defined creationism as involving the creation of all living things in six 24-hour days by a supreme being, as in the literal interpretation of the first chapter of Genesis in the Bible. The law excluded other creation accounts. Both states’ laws were struck down by the courts because requiring the teaching of creationism in public schools would establish the teaching of a particular type of religion, thus violating the U.S. Constitution’s first amendment, which requires separation of church and state.

“Creation science,” also called intelligent design, is not science because it does not follow scientific methods. The claim that a deity created the world cannot be tested. Thus, it is not a hypothesis. Furthermore, some creationists resist modifying their model even when observations fail to support it. The idea of creation by a supreme being is a matter of faith, not of science. This does not mean that creationism is wrong, only that it is not science.

The theory of evolution by natural selection says nothing about the existence of a supreme being. Some people believe that Charles Darwin must have been an atheist to propose his theory. Darwin’s book, *The Origin of Species* (second and subsequent editions), refutes this charge. Darwin recognized that the question of a deity is a religious, and not a scientific one. Deities cannot be investigated scientifically, and, therefore, are outside the realm of science.

**FIGURE P.14**

Alternative medicine. Unproven “natural medicinal herbs,” “healing” crystals, and “aromatherapy” oils. Extraordinary claims should be viewed with skepticism. Is it likely that the makers of these products are adhering to the principles of science?

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**ETYMOLOGY**

pseudo-  = false or sham (Greek)

As you deal with biological issues in this course, and throughout your life, ask at least five basic questions.

1. **What is the question?** Identify the critical question and find out what it really means before you attempt to answer it.
2. **What are the data and how were they obtained?** Determine what the facts are before you attempt to make a decision. Learn to separate data from opinions. Be sure that the data were gathered in a scientific manner and can be validated.
3. **What do the data mean?** Determine if the data support the arguments that are being offered on several sides of an issue. Again, it is important to separate facts from opinions.
4. **Who is reporting the data?** Not all people are reliable sources for data. Determine the credentials of persons who claim to be experts on an
issue. Is this person reporting as a scientist or as someone with personal interests? Learn to question everyone but especially those who do not have the background to know the relevant data and understand the scientific aspects of problems you will be investigating. Most important, remember that even experts can make mistakes. To reduce mistakes, scientists routinely participate in teams to evaluate and eliminate possible sources of bias in the design of investigations and data analysis. Their findings are often subjected to peer-reviewed scientific journals so that others may evaluate and analyze the findings.

5. How complete is the present state of knowledge? Is our knowledge about a subject sufficient to answer the question?

These five questions also can help you connect new information to what you already know. Such connections can increase your understanding of basic concepts in biology and other areas. Establishing these connections can help you detect errors in logic or fact—a crucial ability when you must make important decisions.

For example, discoveries about the chemical substances that make up living things help scientists connect theories about evolution and heredity with their understanding of atoms and molecules. Experiments have revealed that inherited traits are encoded in the chemical structure of DNA molecules. Scientists and engineers have used their knowledge of DNA to make GeneChip® DNA microarrays, such as the one in the photo that opened this chapter. The color of each square in the microarray indicates whether the DNA attached there matches part of the DNA being tested. This medically useful technology depends on a chemical theory of heredity based on the structure of DNA. A continuous web of theories and experimental results that support them connects this theory with scientific explanations of heredity and with Darwin’s evolving theory of evolution.

In addition to the science you will learn in this course, your own ethics, feelings, and values also will affect every decision you make. As you study biology this year and learn about the molecular basis of life, you will be able to examine closely your positions on some controversial issues. As you do so, you will be developing skills that will serve you for the rest of your life—and in many areas, not just in the study of biology.

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Check and Challenge

1. Describe the characteristics of science.
2. What is pseudoscience, and how does it differ from science?
3. Why is creationism considered pseudoscience?
Summary

Knowledge of biology increases every day and presents everyone with new choices. An understanding of biology at the cellular and molecular level is crucial if we are to make educated and informed decisions about biological issues that affect us individually and as a society. These issues include AIDS and the appropriate uses of human growth hormone, now easily available through the techniques of genetic engineering.

By using scientific methods, you can discover new ways to examine life around you. Darwin used scientific methods to develop the theory of evolution by means of natural selection. He made observations and assumptions and developed a theory to explain them. His theory has withstood years of testing and serves as a model for explaining and predicting observations in biology.

Science is one of many different and valid ways to look at the world. The characteristics of science determine what qualifies as science. Science is based on the assumption that the natural world can be investigated and explained. Pseudoscience is false science. One example of pseudoscience is creationism; it is largely a matter of faith, and its assumptions cannot be investigated or rejected by the methods of science.

Science is a means of answering questions. Learning to analyze the nature of a question, to interpret data, and to assess the reliability of a source will help you evaluate new information. Developing connections between new knowledge and what you already know can help you detect errors in logic and the content of new material. With increased knowledge, you are more prepared to cope with the moral and ethical issues raised as a result of the growth of scientific knowledge.

Key Concepts

Make a list of the major concepts you have learned in this chapter. Group the terms so related ideas are together.

Reviewing Ideas

1. Explain the relationships among technology, biology, and ethics.
2. Give some examples of how biology affects your life.
3. How does an understanding of cells and molecules relate to treating or preventing AIDS?
4. How are hypotheses, observations, and experiments used in science?
5. What are the principles behind the theory of evolution by means of natural selection?
6. How did Darwin use the methods of science to develop his theory?
7. Why were Lamarck's ideas rejected? On what assumptions were his ideas based?
8. Compare and contrast a hypothesis and a theory.
9. What is the relationship between natural selection and the environment?
10. What are the characteristics of science, and how does it differ from pseudoscience?
11. What type of questions should you ask when considering biological issues, and why?

Using Concepts

1. Imagine you are going to investigate the origin of Earth. How would you go about it? What would have to be done? What problems would you encounter?
2. Some animals, such as the arctic fox and the ptarmigan (a bird), change the color of their fur or feathers from summer to winter. Relate these changes to natural selection.

3. Darwin stated that a struggle for existence—for adequate food, space, water, and so on—occurs in all species. Is this true for the human species as well? Give concrete examples to substantiate your answer.

4. Why does biological research require good observational skills?

5. Observe and prepare a list of the objects in your classroom. Based on your observations, develop a hypothesis about the uses of that room.

6. Identify several acquired characteristics that you think are not inherited. Verify your list by consulting genetics textbooks.

7. Observe your classmates. What variations can you identify among them?

8. Identify several moral or ethical questions that occurred to you while reading this chapter.

9. Imagine a long-legged wolf and a short-legged wolf. Relate the length of their legs to their ability to catch enough rabbits to feed their offspring. Would one wolf be more successful than the other in providing enough food for its offspring to survive? Would it be advantageous to have long legs?

10. Identify two ways that scientists address bias in their research.

Extensions

1. Choose a biological topic of interest and define a problem or question you have about that topic. State the problem or question as a hypothesis. Now design a test for the hypothesis. What experiment(s) will you do? What methods will you follow?

2. Draw a sketch that illustrates natural selection in progress. Be sure to show some environmental conditions that might favor the adaptations you depict.

Web Resources

Visit BSCSblue.com to access
- Information about the nature of science
- Information about evolution and its role in biology, teaching, and the creationist controversy
- The difference between science and pseudoscience
- Web links related to this chapter
C H A P T E R S

1 The Chemistry of Life
2 Energy, Life, and the Biosphere
3 Exchanging Materials with the Environment
4 Autotrophy: Collecting Energy from the Nonliving Environment
5 Cell Respiration: Releasing Chemical Energy
nonliving things are passive; they cannot control how the environment affects them. Living things, in contrast, select what they absorb and what they retain or release. How do they do this? This is an important question that biologists, scientists who study living things, try to answer. In this unit, you will learn some important ideas that scientists use to understand life. In particular, you will learn about the molecular approach to biology. This approach seeks to answer these questions by using the laws of chemistry and physics that describe all things, not just living ones.

This unit is your introduction to the molecular approach. Here you will learn about the substances that make up living things and how energy drives their activities. You will find out how living things selectively take in some substances from their environment, while rejecting or releasing others. Finally, this unit will explain how living things collect energy from the environment and use it to survive.
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LEARNING OUTCOMES
By the end of this chapter you will be able to:
A  Explain the relationships among atoms, molecules, elements, and compounds.
B  Describe the types of chemical bonds.
C  Explain the pH scale and its use.
D  Relate the characteristics and functions of the four classes of macromolecules.
E  Recognize the importance of nucleic acids in inheritance.
From the time of ancient Greece until the eighteenth century, most educated people believed that all things were made of earth, fire, air, and water. A brilliant scientist named Lavoisier challenged that thinking with his discovery that fire is not a substance but rather a process (combustion) that can convert matter from one form to another. Lavoisier used physical laws and measurement to understand how chemicals react. In doing so, he founded modern chemistry.

Over time, biologists began to recognize that all organisms (living things) are composed of chemicals and that an understanding of life requires an understanding of chemistry. Biochemistry—the chemistry of living organisms—plays a central role in our understanding of today’s biological questions. Information about causes and treatments of cancer, AIDS, and mental illness is being found in the biochemistry of human cells. Evolutionary relationships are being more clearly defined through comparisons of chemicals in different organisms.

This chapter presents some principles of general chemistry and of biochemistry that are important for an understanding of how living cells function.
1.1 Atoms, Molecules, and Compounds

Water is abundant on Earth today, and it exists in three physical states—as a gas, as a liquid, and as a solid. The physical state of water depends on temperature. If the temperature is high enough, water is a gas. If the temperature is low enough, water freezes and forms ice. Although the forms of water may vary, its chemical composition remains the same. Water has some unusual physical and chemical properties that have had a powerful effect on the evolution of life. This may seem surprising, but living things are mostly water. Thus a close look at the chemistry of water can provide information about the chemical nature of matter and about the function of organisms.

Suppose you found a way to subdivide a drop of water into smaller and smaller droplets until you could not see them even under a microscope. No matter how small the water droplet, it would still be made of identical units called molecules. Molecules of water are the smallest units into which water can be subdivided and still have the essential chemical properties of water.

When an electric current flows through water under proper conditions, a remarkable change occurs: water becomes two gases. One is the lightest gas, hydrogen, which burns with a very hot flame in air. The other gas is oxygen. Thus under certain conditions, water molecules can break down into two different substances (which are also molecules), hydrogen and oxygen. Neither substance has the appearance or any other property of water (Figure 1.1).

Hydrogen and oxygen are elements—substances that cannot be broken down chemically into simpler substances. In 1805, the British teacher and chemist John Dalton finished a long series of experiments and measurements...
that indicated every element is made of minute particles. Dalton believed these particles could not be broken into smaller particles, so he named them atoms. **Atoms** are the smallest unit of an element that still has the chemical properties of that element. Dalton stated several principles to describe an atom’s chemical behavior. Those principles form the basis of the most important of all chemical theories, the atomic theory. New data have changed the atomic theory since Dalton’s time, but this theory is still basic to an understanding of chemistry and biology.

Molecules are made of atoms (the smallest units of elements) that have combined chemically. Molecules may be made from more than one type of atom (in which case the molecule is called a compound, such as water), or from atoms of the same type. For example, hydrogen gas consists of hydrogen molecules, each of which consists of two hydrogen atoms linked together (see Figure 1.2). Similarly, an oxygen molecule consists of two oxygen atoms. (Oxygen also forms molecules of ozone, which contain three atoms of oxygen.) Elements can combine chemically in many ways to form the millions of compounds that give Earth its variety of materials.

Chemists have given each element a symbol of letters from the element’s name. H stands for hydrogen, O for oxygen, C for carbon, and N for nitrogen. Iron, however, has two letters. Its symbol is Fe, derived from the word *ferrum*, reflecting that some symbols come from an element’s Latin or Greek name. (See Appendix 1A, “The Periodic Table of the Elements.”)

Despite all the variety of materials, organisms are made of a limited number of compounds, of which water is the most abundant. About 97% of the compounds present in organisms contain only six elements—carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), and sulfur (S). The remaining 3% contain small amounts of other elements. The basic six elements are essential to every organism. Some 20 others are essential, too, but only in smaller amounts (Figure 1.3).

The number of atoms of each element in a molecule is shown by the number, called a subscript, following the symbol for the element (the number 1 is always understood and not written). For example, the formula for carbon dioxide, CO₂, means that a molecule of this gas contains one carbon atom and two oxygen atoms. A molecule of ammonia, written as NH₃, contains one nitrogen atom and three hydrogen atoms. The formula tells what elements are in each molecule and how many atoms of each element the molecule contains.

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**ETYMOLOGY**

**a-** = not (Greek)
**tomo-** = cut or divide (Greek)

An **atom** is a particle that cannot be divided into smaller particles of the same substance.

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**CONNECTIONS**

The presence of the same six elements in all living organisms is an example of patterns in nature.

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**FIGURE 1.2**

Structures of some simple molecules. Molecules of water, hydrogen, and oxygen are made from combinations of atoms, as shown in these models.

**FIGURE 1.3**

Elements present in the human body. The large proportions of hydrogen and oxygen reflect the fact that living organisms consist mostly of water. The dry matter in organisms consists mostly of various compounds of carbon with other elements, especially hydrogen, oxygen, and nitrogen.
Atoms are made up of subatomic particles; these particles are smaller than, or “below” the level of atoms.

**ETYMOLOGY**

**sub**- = below or under (Latin)
Atoms are made up of subatomic particles; these particles are smaller than, or “below” the level of atoms.

1.2 The Structure of Atoms

Although Dalton didn’t know it, atoms themselves are built of many smaller subatomic particles. The subatomic particles of atoms that are basic to an understanding of biology are electrons, protons, and neutrons. The electron carries a negative electric charge. A proton has a positive charge, and a neutron has no charge (it is neutral).

Protons and neutrons remain in the center, or nucleus, of the atom. The electrons, however, seem to be everywhere at once except in the nucleus. The rapidly moving electrons form a negatively charged “cloud” around the nucleus. Electrons tend to stay in this cloud because their negative charges are attracted to the positive charges of the protons in the nucleus. Electrons are distributed throughout the cloud based on differing levels of energy (or attraction) called electron shells. Electrons in shells near the nucleus are held more tightly than those in shells farther from the nucleus.

The simplest of all atoms is hydrogen. A hydrogen nucleus has a single proton, no neutron, and a single electron that orbits in the energy shell closest to the nucleus (Figure 1.4a). Because two electrons can fit in that shell, hydrogen has room for another electron. That vacancy makes hydrogen very reactive.

Atoms of other elements are more complex than the hydrogen atom. For example, an atom of carbon (Figure 1.4b) has six protons and six neutrons in its nucleus and six electrons orbiting the nucleus (two in the innermost shell, four in an outer shell). The number of neutrons may vary, but carbon atoms always contain six protons. Similarly, nitrogen has seven protons and seven electrons, and oxygen has eight protons and eight electrons (Figure 1.4c, d). In both nitrogen and oxygen, there are two electrons in the innermost shell. Nitrogen has five electrons in its outer...
shell, and oxygen has six in its outer shell. That second shell can hold eight electrons, as can the third shell. Atoms with filled electron shells, such as helium and neon, are more stable than atoms with unfilled shells, such as nitrogen and oxygen.

Every atom has an equal number of protons and electrons. Thus, the charges are balanced, and the atom itself has no overall electric charge. However, the atoms of most elements can undergo chemical change by gaining, losing, or sharing one or more electrons with other atoms. Atoms with unfilled shells have a strong tendency to lose or gain electrons to complete their outer shells. As you will see in the next section, this is the basis of chemical reactions.

Atoms of different elements differ in their number of protons, neutrons, and electrons. Atoms of the same element always have the same number of protons and electrons, but they may differ in their number of neutrons. Atoms of the same element that differ in their number of neutrons are called isotopes. For example, 99% of oxygen atoms are like the one in Figure 1.4d. This atom is called the oxygen-16 isotope, named for the sum of its 8 protons and 8 neutrons. Oxygen-17 and oxygen-18 also exist, with 9 and 10 neutrons, respectively. Some isotopes have unstable atomic nuclei that break down, releasing radiation energy. These isotopes are called radioisotopes. They are useful in biological research because they can help to determine some of the chemical reactions organisms carry out. (See Appendix 1B, “Radioisotopes and Research in Biology.”)

**Check and Challenge**

1. What is the relationship between atoms and elements?
2. What are the particles of an atom and how do they interact?
3. What six elements are most important in organisms?
Reactions in Living Cells

1.3 Chemical Reactions

Chemical bonds are the attraction, sharing, or transfer of outer shell electrons from one atom to another. Those bonds between atoms can be broken, the atoms rearranged, and new bonds formed. A chemical reaction involves the making and breaking of chemical bonds. During a chemical reaction, substances interact and form new bonds and new substances.

Only electrons in the outer shells of the atoms pictured in Figure 1.4 are involved when the atoms react during a chemical change. For atoms with electrons in more than one energy shell, only the outermost electrons normally interact during chemical changes. The outer electrons are a reliable indicator of the reactivity of an atom, but the structure of the entire atom also influences chemical reactions.

Chemical reactions occur in the cells of all living organisms. Cells are the basic units of life, much as atoms are the basic units of matter (Figure 1.5). Chemical reactions are important to a cell for two reasons. First, they are the only way to form new molecules that the cell requires for such things as growth and maintenance. Second, the making and breaking of bonds involves changes in energy. As a result of chemical reactions in a cell, energy may be stored, used to do work, or released.

Chemical reactions can be represented as short statements called chemical equations. For example, the breakdown of water can be represented by the following equation:

$$2 \text{H}_2\text{O} \xrightarrow{\text{electric energy}} 2\text{H}_2 + \text{O}_2$$

Why is it necessary to use two molecules of water in the equation? Remember that hydrogen and oxygen molecules each consist of two atoms. A single molecule of water does not yield enough oxygen atoms to make an oxygen molecule, but two molecules of water do. The equation is written to

**FIGURE 1.5**
A generalized animal cell. A membrane encloses all cells. In animals, the genetic material is enclosed in a structure called the nucleus.
balance the number of atoms on both sides of the arrow. Balancing chemical equations illustrates one of the most basic laws of chemistry: the law of conservation of matter, which states that matter is neither created nor destroyed in chemical reactions.

The direction of the arrow in a chemical reaction points from reactants to products. Notice that the number of molecules is shown by a numeral preceding the formula for the molecule. Figure 1.6 shows models that represent chemical reactions.

When molecules collide, they may or may not react, depending on the energy and orientation of the molecules. Activation energy is the energy needed to get a chemical reaction started. Sometimes an outside source of extra energy is necessary to initiate a reaction. For example, hydrogen (H\textsubscript{2}) and oxygen (O\textsubscript{2}) gases can be mixed without reacting until a lighted match, a spark, or ultraviolet light adds energy. This relatively small amount of energy causes some hydrogen molecules and oxygen molecules to react to form water. The reaction releases energy that heats the remaining molecules of hydrogen and oxygen, causing them to react to form more water. The reaction is often explosive. The product, water, has less energy than the hydrogen and oxygen gases had separately in the mixture. The difference in energy is accounted for mainly in the form of light and heat produced by the reaction.

1.4 Chemical Bonds

When atoms interact, they can form several types of chemical bonds. One type forms when electrons move from one atom to another atom. This type of chemical bond occurs in many substances, including table salt, also known as sodium chloride (NaCl). As the latter name suggests, table salt is made of two elements, sodium (Na) and chlorine (Cl). When atoms of these two elements react, an electron passes from a sodium atom to a chlorine atom (Figure 1.7). The resulting sodium atom is positively charged, for it has one less electron than protons. It becomes a sodium ion, written as Na\textsuperscript{+}. 

**FIGURE 1.6**  
Models of chemical reactions. In the decomposition of water, twice as many hydrogen molecules as oxygen molecules are produced.
An ion is an atom or a molecule that has acquired a positive or negative charge as a result of gaining or losing electrons. The chlorine atom is negatively charged, for it has one more electron than protons. It becomes a chloride ion, written as Cl\textsuperscript{-}. Note the change in name from chlorine to chloride. An ionic bond is the attraction between oppositely charged ions, such as the sodium chloride bond (Figure 1.7).

In a second type of chemical bond, called a covalent bond, two atoms share one or more pairs of electrons (Figure 1.8). Two atoms of hydrogen join to form a molecule of hydrogen gas (H\textsubscript{2}) by sharing a pair of electrons. This sharing gives each hydrogen atom a filled electron shell. In a molecule of water, each of the two hydrogen atoms shares a pair of electrons with the same oxygen atom. This gives each hydrogen atom two electrons and fills the outer shell of oxygen with eight electrons.

The chemical behavior of water indicates that the atoms do not share the electrons equally. The larger oxygen atom attracts the electrons more strongly than the smaller hydrogen atoms do. If the electrons of a bond are not shared equally, the bond is called a polar covalent bond. In contrast, the electrons in a molecule of hydrogen gas are shared equally, and the resulting covalent bond is said to be nonpolar.

The unequal sharing of electrons in a water molecule gives the oxygen atom a slight negative charge and each hydrogen atom a slight positive charge (Figure 1.9). Such a molecule is known as a polar molecule. The polar nature of water is biologically significant. Most cells and tissues...
contain large amounts of water—up to 95% in some, with an average of 70–80% water throughout all organisms. Molecules must dissolve in water in order to move easily in and between living cells. Polar molecules, such as sugar, and ions, such as Na\(^+\), dissolve in water because of the electric attraction between them and the water molecules. Nonpolar molecules, such as fats and oils, do not dissolve in water.

Polar molecules may form still another type of chemical bond. A weak attraction can occur between a slightly positive hydrogen atom in a molecule and a nearby slightly negative atom of another molecule (or of the same molecule if it is large enough). This type of attraction is called a **hydrogen bond** (Figure 1.10). In compounds found in organisms, hydrogen bonds usually involve hydrogen atoms that are bonded to oxygen or nitrogen. Hydrogen bonds provide an attractive force between water molecules, which explains why water is a liquid at room temperature and not a gas. A large number of hydrogen bonds can be quite strong, but single hydrogen bonds are much weaker than covalent bonds.

### 1.5 Ions and Living Cells

When table salt dissolves in water, the ionic bonds are broken. Na\(^+\) and Cl\(^-\) ions separate, or dissociate, but remain as ions in solution. The positive sodium ion is attracted to the slightly negative end of water, and the negative chloride ion is attracted to the slightly positive end. Sodium ions are important in regulating water balance in organisms. Other ions,

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**Focus On**

## Structural Formulas

Structural formulas are models that show both the number and arrangement of atoms in molecules. In writing structural formulas of compounds, a covalent bond is indicated by a line. For example, the structural formula for hydrogen gas is written \(\text{H—H}\). Sometimes two atoms share two pairs of electrons between them, forming a double bond that is shown by a double line (\(\equiv\)), as in \(\text{O=O}\), carbon dioxide. When three pairs of electrons are shared by two atoms, they form a triple bond that is represented by three lines (\(\equiv\)). For example, the nitrogen gas (\(\text{N}_2\)) that makes up most of the atmosphere consists of pairs of nitrogen atoms joined by a triple bond. Figure 1.11 shows several methods of representing molecules. Note that the molecular formula tells you only the number of atoms of each type present in the molecule, whereas the structural formula indicates how the atoms are bonded. The space-filling and ball-and-stick models provide pictures of the spatial arrangements of the atoms.

### FIGURE 1.10

**Hydrogen bonding.** A hydrogen bond is a weak attraction between a slightly positive hydrogen atom in one polar molecule and a slightly negative atom in another. This water molecule is forming hydrogen bonds with four other water molecules.
including potassium ions ($K^+$) and calcium ions ($Ca^{2+}$), are involved in many reactions inside cells.

When a nonionic compound, such as water, is converted to ions, the process is called ionization. The ionization of water is a vital reaction in living cells. When a water molecule separates, one of its H—O bonds breaks. The result is a positively charged hydrogen ion ($H^+$) and a negatively charged hydroxide ion ($OH^-/H_2O^{10}$). The hydrogen ion—a proton—quickly combines with a water molecule to form a hydronium ion ($H_3O^+$). It still is convenient, however, to refer to the number of hydrogen ions ($H^+$) in a solution, even though that really means the concentration of hydronium ions ($H_3O^+$).

Only about one in every 500 million water molecules ionizes in living cells, yet all life processes depend on this tiny amount of ionization. Indeed, living cells must maintain their internal levels of $H^+$ and $OH^-/H_2O^{10}$ ions within narrow limits, because even small changes greatly influence important reactions.

The level of $H^+$ and $OH^-/H_2O^{10}$ ions in solution is described by a range of numbers known as the **pH scale** (Figure 1.12). The scale runs from 0 to 14. A solution (a mixture in water) that has the same number of $H^+$ and $OH^-/H_2O^{10}$ ions is neutral and has a pH of 7. Pure water has a pH of 7. A solution having more $H^+$ than $OH^-/H_2O^{10}$ ions is acidic and has a pH less than 7 (low pH). A solution that has more $OH^-/H_2O^{10}$ than $H^+$ ions is basic (or alkaline) and has a pH greater than 7 (high pH). Thus a solution with a pH of 2 is highly acidic, and a solution with a pH of 10 is highly basic.

The pH scale is a logarithmic scale. This means that a change of one pH unit is equal to a tenfold change in the level of $H^+$ ions. For example, a solution with a pH of 3 is 10 times more acidic than a solution with a pH of 4. Figure 1.13 shows the pH of several common substances.

**FIGURE 1.13**

The pH of some common substances. Note that most biological substances are slightly acidic (pH 6–7). The greater acidity of soft drinks (pH 3) is partly responsible for contributing to tooth decay.

**FIGURE 1.12**

The pH scale. This scale is used to denote the acidity and alkalinity of solutions.

$\text{pH}$

<table>
<thead>
<tr>
<th>Increasingly basic</th>
<th>Neutral</th>
<th>Increasingly acidic</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>sodium hydroxide</td>
<td>oven cleaner</td>
</tr>
<tr>
<td>13</td>
<td>hair remover</td>
<td>household ammonia</td>
</tr>
<tr>
<td>12</td>
<td>bleach, phosphate detergents</td>
<td>seawater</td>
</tr>
<tr>
<td>11</td>
<td>eggs</td>
<td>blood</td>
</tr>
<tr>
<td>10</td>
<td>milk</td>
<td>urine</td>
</tr>
<tr>
<td>9</td>
<td>normal rainwater</td>
<td>black coffee</td>
</tr>
<tr>
<td>8</td>
<td>tomatoes, grapes</td>
<td>vinegar, soft drinks</td>
</tr>
<tr>
<td>7</td>
<td>gastric juice</td>
<td>milk</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>normal rainwater</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>black coffee</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>tomatoes, grapes</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>vinegar, soft drinks</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>gastric juice</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>milk</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>normal rainwater</td>
</tr>
</tbody>
</table>

$pH$ is important in biology because the pH of a cell’s interior helps regulate the cell’s chemical reactions. As discussed earlier, all cells rely on chemical reactions for growth and survival. Thus, it is not surprising that organisms have ways to control pH and to respond to changes in the pH of their environment (Figure 1.14). For example, certain fungi and bacteria can grow in acidic solutions but not in basic ones. Some marine organisms have become so adapted to the slightly basic pH (7.8–8.6) of seawater that they cannot live in less basic solutions. The pH of normal urine is about 6, but human blood must remain near pH 7.4. Death nearly always results if the blood pH falls to and stays at 6.8 or rises to and stays at 8.0. Failed kidney function is most often the reason a person cannot maintain normal blood pH.
FIGURE 1.14
Adaptations of organisms to differences in soil pH. (a), Conifers (needle-leaf trees) such as these Douglas firs thrive in the acidic soil of Olympic National Forest in Washington state. (b), Deciduous hardwood trees such as oaks, maples, and beeches compete more successfully in the less acidic soil of this forest.

Check and Challenge

1. How are chemical reactions important in cells?
2. Distinguish among the various types of chemical bonds.
3. Describe the law of conservation of matter.
4. Why is pH important to living organisms?
5. How does the polarity of water assist the movement of molecules?

Biochemistry

1.6 Organic Compounds and Life

Many chemical compounds besides water are needed for life to exist. The most important are organic compounds, in which carbon atoms are combined with hydrogen and usually oxygen. Organic compounds frequently also contain nitrogen, sulfur, or phosphorus. A few carbon compounds are not included with organic compounds: carbon dioxide (CO₂), carbon monoxide (CO), and carbonic acid (H₂CO₃).

The word organic was coined long ago when it was thought these compounds could be formed only by living cells. Since then, millions of different organic compounds have been synthesized in the laboratory. There is no longer any reason to call these compounds organic, but the name is so well established that it is still widely used to describe nearly all carbon compounds, essential for life or not.
Carbon atoms can combine in long chains that form the backbone of large complex molecules, or macromolecules. The backbone of carbon atoms is called the carbon skeleton (Figure 1.15). Other atoms and molecules can attach to the carbon skeleton, giving each macromolecule a particular structure and, therefore, a particular function. The following sections of the chapter discuss the characteristics of the four most important classes of molecules in living cells—carbohydrates, lipids, proteins, and nucleic acids. Figure 1.16 shows the relationship between the cell’s building-block molecules and their macromolecular forms.

1.7 Carbohydrates

All known types of living cells contain carbohydrates. In addition to carbon atoms, carbohydrates contain hydrogen and oxygen atoms in the same two-to-one ratio as water. The simplest carbohydrates are single sugars called monosaccharides, which may contain three to seven carbon atoms in their carbon skeletons. Figure 1.17a shows the structural formulas of two forms of the common monosaccharide glucose. Most organisms use glucose (which is also referred to as blood sugar) as a source of energy. The energy in glucose, and in all molecules, is contained in the atoms and bonds of the molecule itself.

Biologically important sugars often have a phosphate group attached to the carbon skeleton and are called sugar-phosphates. The phosphate
group, which is composed of an atom of phosphorus and four atoms of oxygen (see Figure 1.17b).

Two simple sugar molecules, or monosaccharides, (Figure 1.18a) may bond to form a double sugar, or disaccharide, represented in Figure 1.18b. The most familiar of all disaccharides is sucrose, commonly called table sugar. Sucrose contains glucose and another monosaccharide, fructose. Lactose, or milk sugar, is a disaccharide formed of glucose and the monosaccharide galactose. Maltose, or malt sugar, is a common disaccharide made of two glucose molecules.

Several glucose molecules may bond to form complex carbohydrates called polysaccharides (Figure 1.18c). Starch and cellulose are the complex carbohydrates commonly formed by plants. Starch is an energy-storage and carbon-reserve compound in many plants and is an important food source for humans. Cellulose is a structural molecule found in the rigid walls surrounding plant cells, and it is an important part of wood and cotton fibers. The human liver and muscles store carbohydrates in the form of glycogen, also called animal starch. Molecules of starch, cellulose, and glycogen consist of thousands of glucose units and have no fixed size.

![FIGURE 1.16](image)

**FIGURE 1.16**
The building blocks of the cell.
Most macromolecules are polymers—long chains of similar subunits (monomers). For example, proteins are polymers made from many amino-acid monomers. Sugars and polysaccharides are carbohydrates.

![FIGURE 1.17](image)

**FIGURE 1.17**
The structures of a sugar and a sugar-phosphate. (a) In solution, glucose, a 6-carbon sugar, can exist in two forms: a straight chain and a ring form. The ring form, in which five carbon atoms and an oxygen atom form a closed ring, is by far the most abundant. Although not shown, carbon atoms exist at the points of the hexagon. Also, actual glucose molecules are not solid, as depicted; their centers are mostly open space. (b) The two forms of glucose-6-phosphate are shown. Cells often add a phosphate group to glucose after glucose enters the cell.
Lipids, or fats and oils, are macromolecules that have two primary functions: long-term storage of energy and carbon and building of structural parts of cell membranes. Lipids generally do not dissolve in water, because they are nonpolar. Like carbohydrates, lipids contain carbon, hydrogen, and oxygen, but not in a fixed ratio. Building blocks of lipids, called fatty acids and glycerol, make up the simple fats most common in our diets and bodies. Three fatty-acid molecules and one glycerol molecule join to form a simple fat, or triglyceride, as shown in Figure 1.19.

The biologically important properties of simple fats depend on their fatty acids. For example, the fats in meat are different from the oils in vegetables because the fatty acids are different. The properties of fatty acids, in turn, depend on the length of the carbon chains and the type of bonds between the carbons. Common fatty acids have a total of 16 or 18 carbon atoms. Fatty acids in which single bonds join the carbon atoms are saturated fatty acids (one way to remember this: the carbon atoms are saturated with hydrogens). Unsaturated fatty acids are fatty acids in which double bonds join some of the carbon atoms. Figure 1.19 shows both types of fatty acids.

Unsaturated fats (fats containing unsaturated fatty acids) tend to be oily liquids at room temperature. Olive oil, corn oil, and sunflower oil consist
mostly of unsaturated fats. Saturated fats tend to be solids at room temperature. Butter and lard consist mostly of saturated fats. Fats are a more efficient form of energy storage than are carbohydrates because fats contain a larger number of hydrogen atoms and less oxygen. You will learn later how the amount of hydrogen and oxygen in fats and carbohydrates relates to energy, as well as the important roles that saturated and unsaturated fats play in the diet.

Two other types of lipids important in cells are phospholipids and cholesterol. Phospholipids form when a molecule of glycerol combines with two fatty acids and a phosphate group (Figure 1.20a and b). The polar phosphate group allows one end of the lipid molecule to associate with water. Together with proteins, phospholipids form cellular membranes (Figure 1.20c). Membranes are critical to cell survival because they separate a cell’s internal chemical reactions from the outside environment. They also help control which chemicals enter and leave the cell. Cholesterol (Figure 1.20d) is part of the membrane structure of animal cells and is important in nutrition. Cells in the human body manufacture many essential substances, such as sex hormones, from cholesterol.

**1.9 Proteins**

Every living cell contains from several hundred to several thousand different macromolecules known as **proteins**. Proteins are structural components of cells as well as messengers and receivers of messages (also called receptors) between cells. They play an important role in defense
against disease. Skin, hair, muscles, and parts of the skeleton are made of proteins. Their most essential role, however, is as enzymes, specialized molecules that assist the many reactions occurring in cells.

Cells make proteins by linking building blocks called amino acids. Amino acids are small molecules that contain carbon, hydrogen, oxygen, and nitrogen atoms; two also contain sulfur atoms. Figure 1.21 shows the general structural formula for an amino acid. Amino acids have a central carbon atom to which is attached a hydrogen atom, an amino group (—NH₂), an acid group (—COOH), and a variable group, symbolized by R, which may be one of 20 different atoms or groups of atoms. Observe in Figure 1.22a that in the amino acid glycine, R is an H atom, and in alanine, R is a —CH₃ group. Some R groups are polar, such as the amino group in lysine; others are nonpolar, such as the carbon chain in leucine. The polarity of amino acids affects their ability to dissolve in water.

Any two amino-acid molecules may combine when a chemical bond forms between the acid group of one molecule and the amino group of the
other (Figure 1.22a). Covalent bonds of this sort, formed between amino acids, are called **peptide bonds**. Additional peptide bonds may form, resulting in a long chain of amino acids, or **polypeptide** (Figure 1.22b). Longer polypeptide chains form proteins; protein molecules range from about 50 to 3,000 amino-acid units. The type, number, and sequence of its amino acids distinguishes a protein from all others.

The sequence of amino acids in a polypeptide chain forms the **primary structure** (Figure 1.23a) of a protein. In most proteins, the chain folds or twists to form local structures known as **secondary structures** (Figure 1.23b). The most common secondary structures, alpha helices and beta sheets, are stabilized by hydrogen bonds. More complex folding creates a **tertiary structure** (Figure 1.23c), which usually is globular, or spherical. One of the major forces controlling how a protein folds is **hydrophobicity**, or the tendency for nonpolar amino acids to avoid water. As a result, nonpolar amino acids tend to be buried inside folded proteins, where they are shielded from contact with water. Some proteins have nonpolar amino acids on the outside, where they can interact with lipid membranes.

The sequence of amino acids in a protein (primary structure) determines its three-dimensional shape (secondary and tertiary structure). The tertiary structure, in turn, determines a protein’s function. Each individual protein has a unique shape and, therefore, a specific function. A few proteins

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**FIGURE 1.22**

**Formation of a polypeptide.** A peptide bond forms when the acid group (—COOH) of one amino acid joins to the amino group (—NH₂) of another amino acid (a). The acid group loses an atom of hydrogen and an atom of oxygen. The amino group loses an atom of hydrogen. These atoms combine to form a water molecule. More peptide bonds can form in the same way, joining a chain of amino acids to form a polypeptide (b).
become active only when two or more tertiary forms combine to form a complex quaternary structure (Figure 1.23d). Specific geometric and chemical interactions determine which surfaces of the proteins combine to create the quaternary structure.

1.10 Nucleic Acids

Nucleic acids are macromolecules that dictate the amino-acid sequence of proteins, which in turn control the basic life processes. Nucleic acids also are the source of genetic information in chromosomes, which are passed from parent to offspring during reproduction. Nucleic acids are thus the chemical link between generations, dating back to the beginning of life on Earth. How can one type of molecule play such a dominant role in all living things? The answer lies in the structure of the molecules.

Nucleic acids are made of relatively simple units called nucleotides connected to form long chains. Each nucleotide consists of three parts. One part is a 5-carbon sugar (a pentose), which may be either ribose or deoxyribose. Compare the structural formulas in Figure 1.24. What differences can you see? Attached to the sugar is a nitrogen-containing base,
which is a single or double ringlike structure of carbon, hydrogen, and nitrogen (Figure 1.25). The third part of a nucleotide is a phosphate group $\text{P}$ (see Figure 1.26).

Nucleic acids that contain ribose in their nucleotides are called ribonucleic acids, or RNA. Nucleotides containing deoxyribose form deoxyribonucleic acids, or DNA. In DNA, each of the four different nucleotides contains a deoxyribose, a phosphate group, and one of the four bases—adenine, thymine, guanine, or cytosine. The possible DNA nucleotides that can form from these bases are illustrated in Figure 1.26. Figure 1.27 shows a chain of nucleotides connected to form a nucleic-acid molecule.

**FIGURE 1.25**
Four nitrogen bases that occur in nucleotides. In this book, symbols are used to represent the nucleotides adenine, guanine, cytosine, and thymine. Note that cytosine and thymine have a single-ring structure; adenine and guanine have a double ring.

**FIGURE 1.26**
The components of DNA. Each nucleotide contains one of the bases, one sugar, and one phosphate group. The sugar is deoxyribose, making these the four nucleotides of DNA.

**FIGURE 1.27**
A short section of a model of nucleic acid. The bases adenine, guanine, thymine, and cytosine are attached to a backbone of alternating deoxyribose sugar and phosphate groups.
RNA is a nucleic acid much like DNA, except that it contains the sugar ribose instead of deoxyribose. Also, in RNA the nitrogen base uracil, shown in Figure 1.28, replaces the base thymine. The other three bases, adenine, guanine, and cytosine, are the same in RNA and DNA.

Structurally, there is another difference between DNA and RNA. DNA always occurs in cells as a double-stranded helix (Section 1.11); RNA is single stranded, although it can fold into complex shapes. There are three types of RNA in cells, each of which performs a different role in the synthesis of proteins.

The number and arrangement of the nucleotides vary in RNA as they do in DNA. The different arrangements of nucleotides in a nucleic acid provide the key to how these molecules contribute to the diversity of organisms living on Earth.

**Check and Challenge**

1. Describe how building-block molecules combine to form each of the four types of biological macromolecules.
2. What is the relationship between the primary and tertiary structure of a protein?
3. Describe the three-part structure of a nucleotide.
4. How do the chemical structures of ribose and deoxyribose differ?
Genetic Coding in Cells

1.11 The Double Helix

In a short scientific paper published in 1953, James Watson and Francis Crick (Figure 1.29a and b) proposed a model for the structure of the DNA molecule that is still accepted today (although with some modification). They founded their model on the principle of specific pairing of the nucleotides, shown in Figure 1.30. Hydrogen bonds form only between the nucleotide bases of adenine (A) and thymine (T) or cytosine (C) and guanine (G). In other words, there is a specific interaction between the surfaces of the nucleotide molecules. Experiments done by Rosalind Franklin (Figure 1.29c) in the laboratory of Maurice Wilkins (Figure 1.29d) suggested to Watson and Crick that DNA molecules have a double-helix structure.

The DNA double helix is composed of two long chains of nucleotides. The nucleotides of each chain are connected between their deoxyribose sugars by phosphate groups. (This forms a so-called sugar-phosphate backbone.) The two chains run next to each other, but, chemically speaking, the sugar-phosphate backbones run in opposite directions. The two chains are connected by hydrogen bonding between nitrogen bases to form a long double-stranded molecule. Because of the specific pairing between bases,
each strand is the complement of the other. For example, a guanine on one strand indicates the presence of cytosine on the other strand, and vice versa. (As you will see later, complementarity is the basis for copying DNA.) The two strands intertwine, forming a double helix that winds around a central axis like a spiral staircase (Figure 1.31). As mentioned earlier, RNA also can fold into complex shapes, although those shapes result from interactions within a single-stranded molecule (or with proteins). Nonetheless, the folds in RNA are held together by the same type of base pairing as in DNA (Figure 1.32).

1.12 The Functions of DNA

DNA forms the genes, units of genetic information, that pass from parent to offspring. The structure of DNA explains how DNA functions as the molecule of genetic information. In brief, DNA stores information...
in a code consisting of units that are three nucleotides long; these short sequences are called triplet codons. Certain codons are translated by the cell to mean certain amino acids. For example, the codon GGA means glycine when translated by the cell. Thus the sequence of nucleotides in DNA can indicate a sequence of amino acids in protein. As you have seen, the sequence of amino acids in a protein determines its shape, which then
The Scanning Tunneling Microscope

Electron microscopes are powerful tools for exploring the structure of microscopic objects such as cells. Unlike light microscopes, which use light and glass lenses to make details visible, electron microscopes use electron beams and magnetic coils. Electron microscopes permit much greater magnification of cellular structures than do light microscopes. The scanning tunneling microscope uses electrons already in the sample, rather than an external electron beam. This allows scientists to see surface structures clearly. A characteristic of all materials is that some electrons form an electron cloud around the material. The scanning tunneling microscope probes this electron cloud to reveal structure.

To scan the surface of a sample, the tip of the microscope (a needle) is pushed toward the sample until the electron clouds of the tip and the sample touch. Then an electric voltage is applied between the tip and the sample, causing electrons to flow through a narrow channel in the electron clouds. This electron flow is called the tunneling current. The tunneling current is extremely sensitive to the distance between the microscope tip and the surface of the sample and allows precise measurements of the vertical surface features of the sample. A feedback mechanism maintains the tip at a constant height as it sweeps across the sample surface, following the contours of the surface atoms. The motion of the tip is read and processed by a computer and displayed on a screen. A three-dimensional image of the surface is obtained by sweeping the tip in parallel lines (see Figure 1.33). To achieve high-resolution images of surface structures, the microscope must be shielded from even the smallest of vibrations, such as a footstep or sound.

Investigators probing the structure of DNA have generated images depicting the helical twists and turns of a strand of DNA (Figure 1.34). Because scanning tunneling microscopes can operate equally well with samples in air or liquid, the DNA can be observed under normal atmospheric conditions. (In an electron microscope, samples must be observed in a vacuum.)

**FIGURE 1.33**
Mechanism of the scanning tunneling microscope. The shape of the electron cloud above a surface reveals the molecular structure of the surface.

**FIGURE 1.34**
A DNA molecule seen with the scanning tunneling microscope, (×200,000). The microscope reveals the shape of the DNA molecule.
Check and Challenge

1. What determines which nitrogen bases form pairs in DNA?
2. If one DNA strand has the sequence AGTTC, what is the sequence of the opposite, or complementary, strand?
3. List four life processes in which DNA plays an important role.
Summary

Chemical reactions occur continuously in cells, the basic units of life. Cells carry out their biological functions through chemical reactions. Elements are materials that cannot break down into substances with new or different properties. They are the basic chemical form of matter. Atoms contain a characteristic number of positively charged protons, negatively charged electrons, and neutral neutrons. All elements are composed of atoms. Ions are atoms or molecules that have gained or lost electrons; ions have a positive or negative charge. Chemical bonds hold atoms together to form molecules. When those bonds involve the sharing of electrons, the bonds are called covalent bonds. When those bonds involve the attraction of two oppositely charged ions, the bonds are called ionic bonds. Weak bonds involving a partially positive hydrogen atom are called hydrogen bonds.

In chemical reactions, molecules interact and form different substances. Those interactions are accompanied by energy changes that drive the reactions living cells use for growth, reproduction, and all other functions. The membranes that surround cells enclose the chemical reactions of the cells and isolate them from the outside environment.

Organisms contain four major types of macromolecules. Carbohydrates store and transfer energy in cells and contribute to cell structure. Lipids store energy and form a major part of membranes. Proteins are structural components of cells, enzymes, and messengers and receivers of messages. The nucleic acids DNA and RNA store, transfer, and direct the expression of genetic information. Chemical compounds have biological activity because of their specific chemical structures. Chemical structure dictates biological function.

Key Concepts

Below is the beginning of a concept map. Use the concepts that follow to build a more complete map. Add as many other concepts from the chapter as you can. Include appropriate linking words.

- atoms
- lipids
- carbohydrates
- macromolecules
- chemical bonds
- molecules
- chemical reactions
- nucleic acids
- proteins
- elements

Reviewing Ideas

1. What type of information does the periodic table of elements provide?
2. State in your own words the relationship among atoms, protons, neutrons, and electrons.
3. What are isotopes and why are they biologically important?
4. How does an ion differ from the atom from which it was formed?
5. Compare ionic, nonpolar covalent, and polar covalent bonds.
6. What is the importance of water in cells?
7. What is meant by pH, and how does pH affect cells and cellular processes?
8. Describe the structure of an amino acid. What type of bond forms the link between amino acids?
9. What are the building blocks of nucleic acids? Why are nucleic acids important in biology?
10. Why are lipids important to cell structure and function?

Using Concepts

1. Using simple molecular models, draw the electric attractions that allow sodium and chloride ions to dissolve in water. (Hint: Represent water as in Figure 1.9.)
2. Distinguish between amino acids and peptides and between simple peptides and polypeptides.
3. You are an analytical chemist working in a nutritional analysis laboratory. Someone brings you a tropical food made of only one type of macromolecule. How would you determine whether it is carbohydrate, fat, protein, or nucleic acid? (Reference: Investigation 1B)
4. You are given two samples of carbohydrates. One contains 6 carbon atoms per molecule (molecular formula C₆H₁₂O₆), and the other contains 12 carbon atoms (C₁₂H₂₂O₁₁). Which one is glucose and which one is sucrose? Explain your answer.
5. Animals usually store energy reserves as lipids; plants store them as polysaccharides. What is the advantage to animals of using lipids as storage molecules?
6. Margarine is produced by hydrogenating liquid vegetable oils so that they become solids like butter. What chemical change has taken place in the fatty acids?

Synthesis

Fat is more abundant in some cells of your body than in other cells. Explain how natural selection could account for that variation.

Extension

DNA is the source of genetic information for all living organisms, but the sequence of DNA nucleotides in organisms differs. In fact, the sequences of DNA can be characteristic for different species. If you were to compare the sequence of DNA nucleotides of similar and dissimilar organisms, what patterns would you observe? How is this evidence of evolutionary relatedness?

Web Resources

Visit BSCSblue.com to access
- Resources to help you understand important chemical concepts and the chemical basis of life
- Explanations and self-tests on biochemistry and an explanation of the chemical basis of your sense of taste and smell
- Web links related to this chapter