CHAPTER 1

Biology: *Exploring Life*

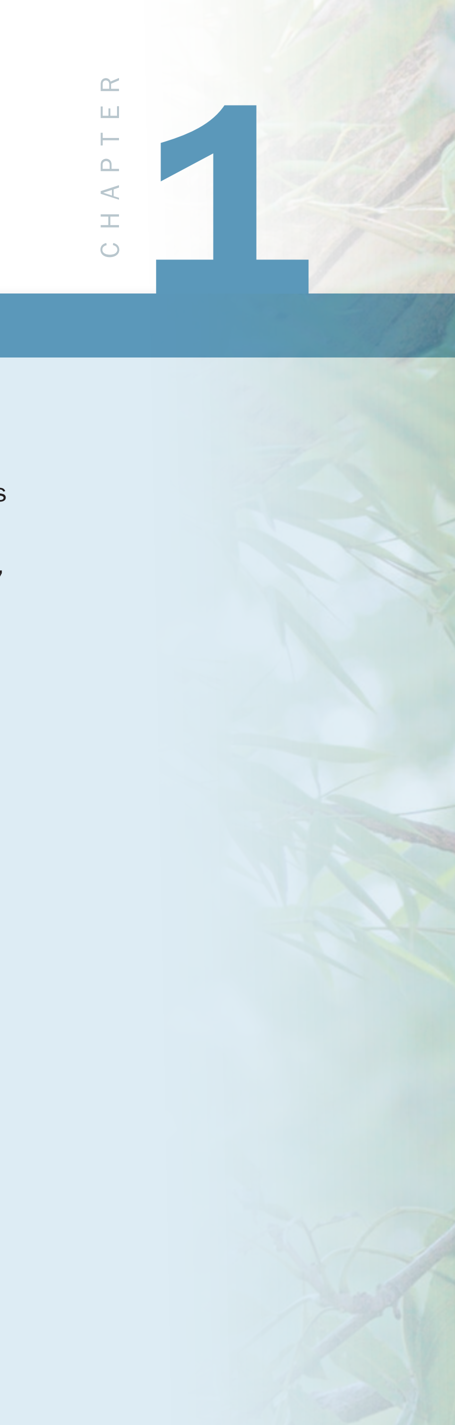
Red pandas (*Ailurus fulgens*), such as the one on the cover of this textbook and the one pictured to the right, have a characteristic kitten-like face and grow to be about the size of a large house cat. These captivating creatures are well adapted for life in the mountainous forests of Asia. Their cinnamon red and white coat camouflages them with the red mosses and white lichens of their environment, while their dark underbelly helps hide them from predators looking up from below. Their long bushy tail helps them balance in the trees and, when wrapped around their bodies, provides warmth during the winter. And a bony projection in their wrist helps them grasp one of their favorite foods, bamboo.

Who are a red panda's closest relatives?

You might think of the much larger, black and white pandas when you think about bamboo-eaters. Giant pandas live in similar regions in Asia. Are they closely related to red pandas? Scientists once thought so but have since reclassified red pandas into their own family. Later in the chapter we'll explore how scientists have traced the family tree of red pandas.

Despite their distinct lineages, the red panda and the giant panda do have something in common—they are both at risk of going extinct in the wild. Scientists don't have an accurate count of the red panda's numbers or know exactly where they live. The most recent counts estimate there are about 10,000 red pandas left in the world, a number that is likely to fall below 9,000 over the next 30 years. Finding and counting these shy, solitary animals in their remote habitats is difficult—just one example of the challenges and adventures encountered in biology, the scientific study of life.

We will begin this chapter by defining biology. Next we'll consider the nature and process of science. And we'll end the chapter with an exploration of five unifying themes that you will find woven throughout your study of biology.



BIG IDEAS

Biology: The Scientific Study of Life (1.1–1.3)

Life can be defined by a group of properties common to all living organisms and is characterized by both a huge diversity of organisms and a hierarchy of organization.

The Process of Science (1.4–1.8)

Science is based on verifiable evidence. In studying nature, scientists make observations, form hypotheses, and test predictions.

Five Unifying Themes in Biology (1.9–1.14)

Themes that run through all of biology are evolution, information, structure and function, energy and matter, and interactions.

Biology: The Scientific Study of Life

1.1 What is life?

Defining **biology** as the scientific study of life raises the obvious question: What is *life*? Even a small child realizes that an ant or a plant is alive, whereas a rock or a car is not. But the phenomenon we call life defies a one-sentence definition. We recognize life mainly by what living things do. **Figure 1.1** explores some of the properties and processes we associate with life.

All organisms, from ants to plants to people, are composed of **cells**—the structural and functional units of life. The phenomenon we call life emerges at the level of a cell: A cell can regulate its internal environment, take in and use energy, and respond to its environment. The ability of cells to give rise to new cells is the basis for all reproduction and for the growth and repair of multicellular organisms. A cell may be part of a complex plant or animal, or it may be an organism in its own right. Indeed, single-celled bacteria and other unicellular organisms far outnumber multicellular organisms on Earth.

Figure 1.1 also illustrates that the living world is wondrously varied. In the next module we see how biologists attempt to organize the remarkable diversity of life.

? How would you define life?

Life can be characterized by its properties and processes, such as those depicted in Figure 1.1.

▲ **Figure 1.1** Some properties of life

1.2 Biologists arrange the diversity of life into three domains

Diversity is a hallmark of life. One way in which biologists make sense of the vast array of organisms existing now and over the long history of life on Earth is to organize life's diversity into groups. Each unique form of life is called a species and is given a two-part, italicized, scientific name. The name identifies the genus and the particular species within that genus. For instance, the name for our species is *Homo sapiens*, meaning "wise man." Biologists have so far identified and named about 1.8 million species. Estimates of the total number of species range from 10 million to more than 100 million.

There seems to be a human tendency to group things, such as snakes or butterflies, although we recognize that each group includes many different species. And we often cluster groups into broader categories, such as reptiles (which include snakes) and insects (which include butterflies). Taxonomy, the branch of biology that names and classifies species, arranges species into a hierarchy of broader and broader groups, from genus, family, order, class, and phylum, to kingdom. A goal of this classification system is to reflect the evolutionary history and relationships of organisms.

Historically, biologists divided all of life into five kingdoms. But new methods for assessing evolutionary relationships, such as comparisons of DNA sequences, have led to an ongoing reevaluation of the number and boundaries of kingdoms. Although the debate continues on such divisions, there is consensus among biologists that life can be organized into three higher levels called **domains**. **Figure 1.2** shows representatives of domains Bacteria, Archaea, and Eukarya.

Domains Bacteria and Archaea both consist of microscopic organisms with relatively simple cells. You are probably most familiar with bacteria, a very diverse and widespread group. Many members of domain Archaea live in Earth's extreme environments, such as salty lakes and boiling hot springs. Each rod-shaped or round structure in the photos of bacteria and archaea in Figure 1.2 is a single cell. These photos were made with an electron microscope, and the number along the side indicates the magnification of the image.

▲ **Figure 1.2** The three domains of life

All the organisms with more complex cells are called eukaryotes and are grouped in domain Eukarya. Protists are a diverse collection of mostly single-celled organisms. Figure 1.2 shows an assortment of protists in a drop of pond water. Biologists continue to assess how to group the protists to reflect their evolutionary relationships.

The three remaining groups within Eukarya are distinguished partly by their modes of nutrition. Kingdom Plantae consists of plants, which produce their own food by photosynthesis. The plant pictured in Figure 1.2 is a tropical bromeliad, a plant native to the Americas.

Kingdom Fungi, represented by the mushrooms in Figure 1.2, is a diverse group whose members mostly decompose organic wastes and absorb the nutrients into their cells.

Animals, which are grouped in Kingdom Animalia, obtain food by eating other organisms. The butterfly in Figure 1.2 is drinking nectar from a thistle flower.

Another way in which biologists make sense of the diversity and complexity of life is to organize it into a hierarchy of structural levels, extending from the microscopic level of cells to the global scale of the entire Earth. In the next module we take a visual journey through these levels.

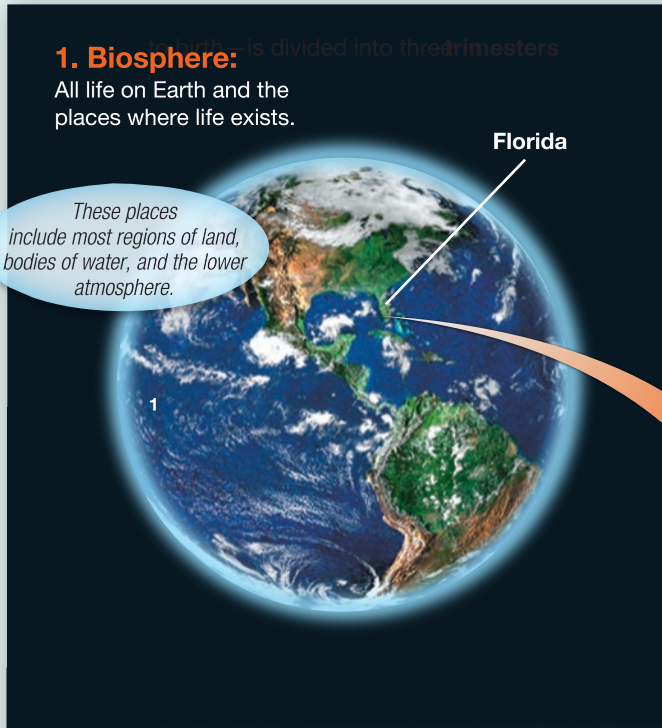
? To which of the three domains of life do we belong?

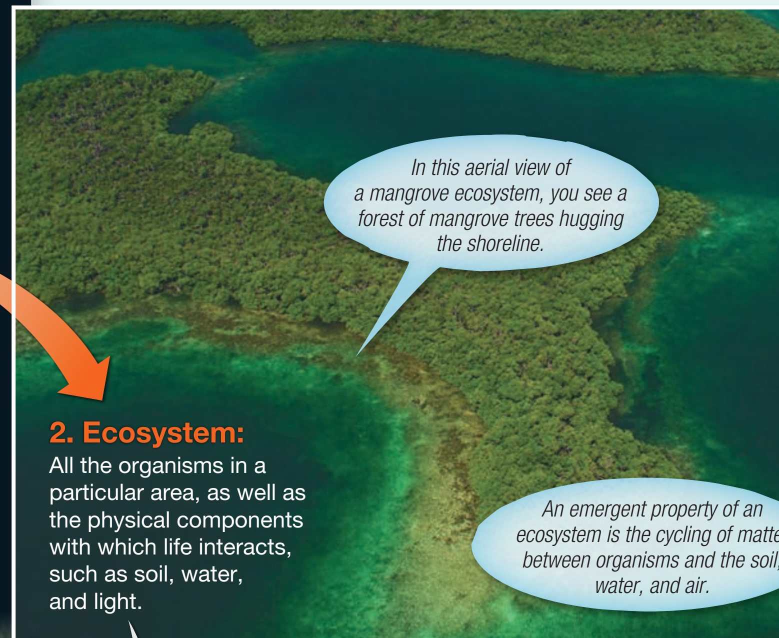
Eukarya

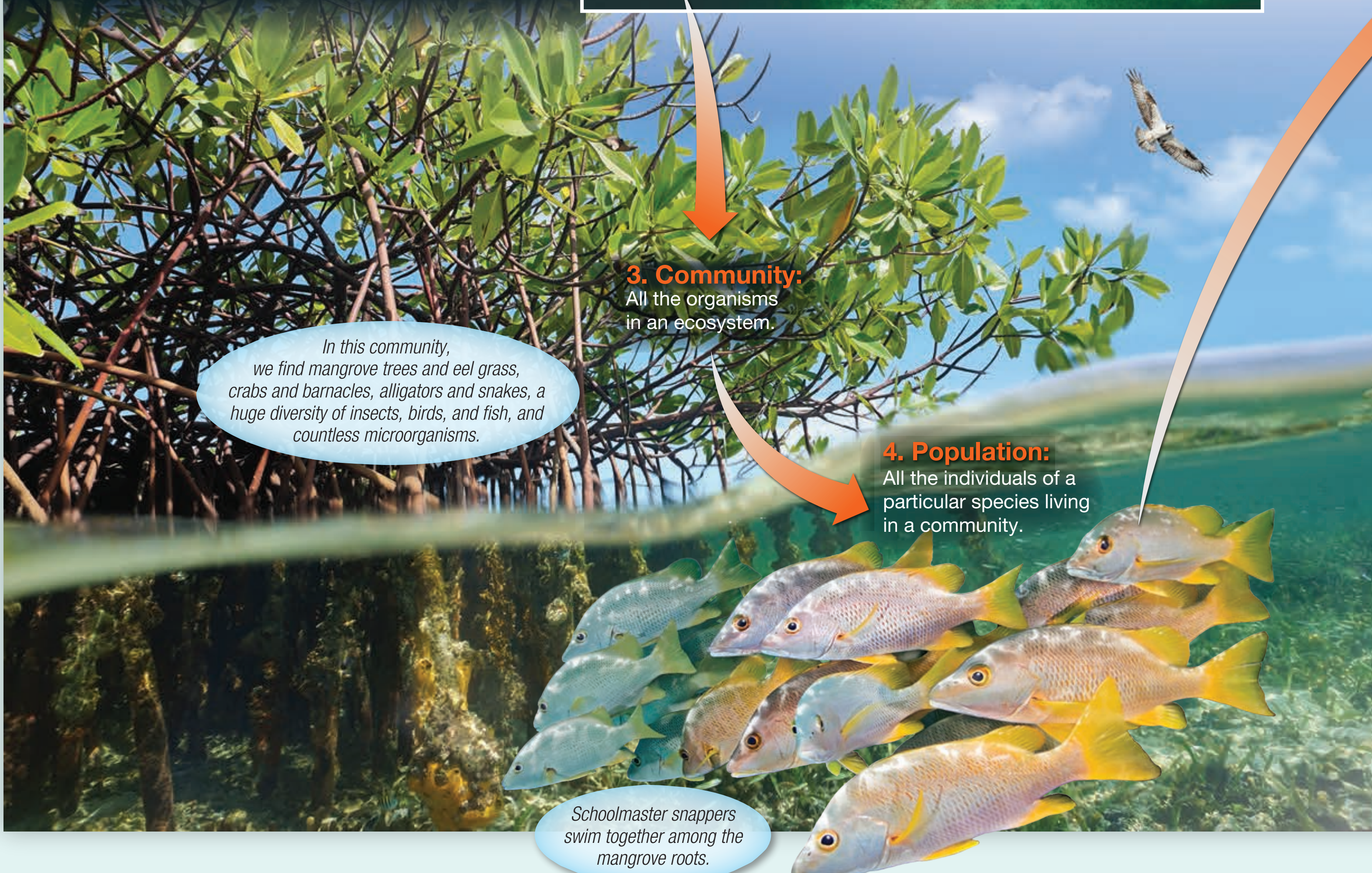
VISUALIZING THE CONCEPT

1.3 In life's hierarchy of organization, new properties emerge at each level

Biologists study life across a very broad range of scales, from the molecules in a cell to the entire living planet. They divide this vast scope of biology into a series of structural

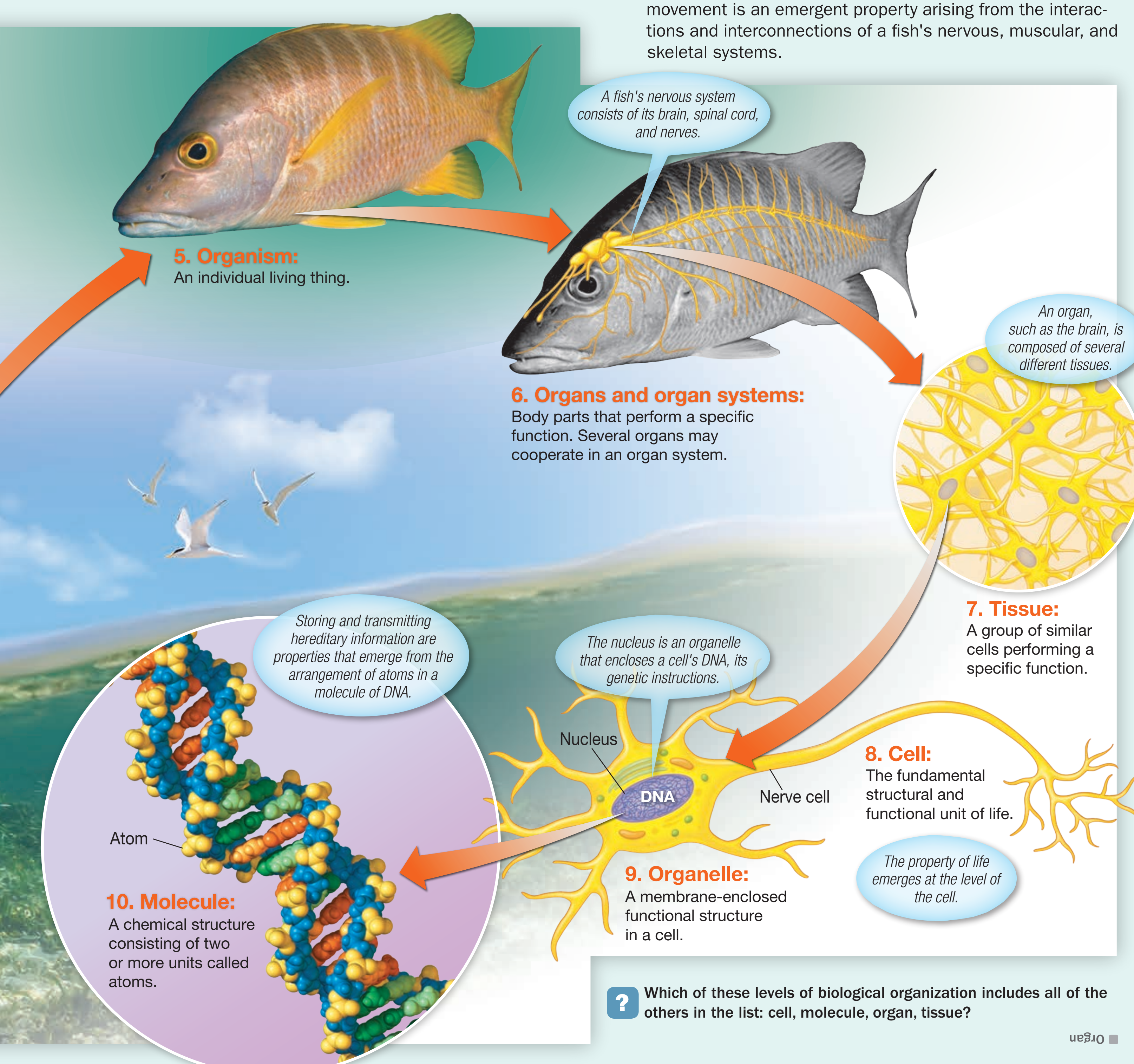






levels. Follow the arrows to take a visual tour down through this organizational hierarchy, using a mangrove swamp in Florida as an example.

Biologists often focus their study of the natural world on one or a few of these levels, exploring individual components and interactions between those components, as well as connections to other levels. Indeed, if we reverse the arrows and move upward through this figure from molecules to the biosphere, we find that novel properties arise at each higher level, properties that were not present at the preceding level. Such **emergent properties** result from the specific arrangement and interactions of component parts. For example, the arrangement and connections of nerve cells enables nervous signals to travel from a fish's brain to its tail. And movement is an emergent property arising from the interactions and interconnections of a fish's nervous, muscular, and skeletal systems.



? Which of these levels of biological organization includes all of the others in the list: cell, molecule, organ, tissue?

■ Organ

The Process of Science

1.4 What is science?

Science is a way of knowing—an approach to understanding the natural world. It stems from our curiosity about ourselves and the world around us. At the heart of science is inquiry, a search for information and explanations of natural phenomena.

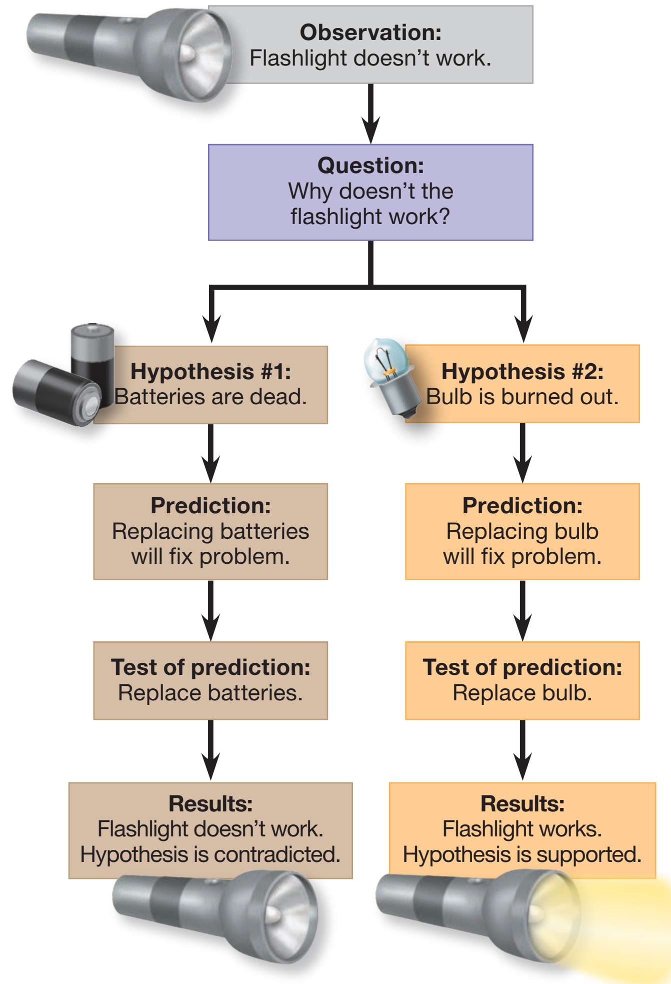
Biology, like other sciences, begins with careful observation. In gathering information, biologists often use tools such as microscopes to extend their senses and precision instruments to facilitate careful measurement. Recorded observations are called **data**—the evidence on which scientific inquiry is based. Some data are *qualitative*, often in the form of recorded descriptions. For example, Jane Goodall spent decades recording her observations of chimpanzee behavior during field research in Tanzania (see Module 35.22). She also recorded volumes of *quantitative* data, such as the frequency and duration of specific behaviors. Quantitative data are generally numerical measurements, which may be organized into tables and graphs and analyzed with a type of mathematics called statistics.

Observations often prompt us to ask questions and then seek answers by forming and testing hypotheses. A **hypothesis** is a proposed explanation for a set of observations, and it leads to predictions that can be tested by making additional observations or by performing experiments. An **experiment** is a scientific test, often carried out under controlled conditions.

We all use hypotheses and predictions in solving everyday problems. Let's say you are preparing for a big storm that is approaching your area and find that your flashlight isn't working. That your flashlight isn't working is an observation, and the question is obvious: Why doesn't it work? **Figure 1.4** presents two hypotheses, each of which leads to predictions you can test. Predictions are the results we should expect if the hypothesis is correct, and they often take an "*if . . . then*" form. For example, *if* the dead-battery hypothesis is correct, *then* replacing the batteries with new ones will fix the problem.

An important point about scientific inquiry is that we can never *prove* that a hypothesis is true. As shown in Figure 1.4, the burned-out bulb hypothesis is the more likely explanation in our hypothetical scenario. But perhaps the old bulb was simply loose and the new bulb was inserted correctly. We could test this hypothesis by carefully reinstalling the original bulb. If the flashlight doesn't work, the burned-out bulb hypothesis is supported by another line of evidence. Testing a hypothesis in various ways provides additional support and increases our confidence in the hypothesis. Indeed, multiple rounds of hypothesis testing may lead to a scientific consensus—the shared conclusion of many scientists that a particular hypothesis explains the known data well and stands up to experimental testing.

How is a theory different from a hypothesis? A scientific **theory** is much broader in scope and is supported by a large and usually growing body of evidence. For example, the theory of evolution by natural selection explains a great diversity of observations, is supported by a vast quantity of evidence, and has not been contradicted by any scientific data.



▲ **Figure 1.4** An everyday example of forming and testing hypotheses

How is science different from other ways of describing and explaining nature, such as philosophy or religion? Those endeavors also seek to make sense of the world around us, and they often play an important role in society. But the scientific view of the world is based on hypothesis testing and verifiable evidence. Indeed, one of the distinguishing characteristics of science is the willingness to follow the evidence—and to correct itself when new evidence is found.

To help you better understand what science is, we include a Scientific Thinking module in each chapter. These modules encompass several broad activities that scientists engage in: observing nature; forming hypotheses and testing them using various research methods; analyzing data; using tools and technologies to build scientific knowledge; communicating the results of scientific research; and evaluating the implications of such studies for society as a whole.

? **What is the main requirement for a scientific hypothesis?**

It must generate predictions that can be tested by experiments or gathering further observations.

1.5 Hypotheses can be tested using controlled experiments

Many animals match their environment: toads the color of dead leaves, green cabbage worms on green leaves, or white snowy owls in their arctic habitat. From these observations, one might hypothesize that such color patterns have evolved as adaptations that protect animals from predation. Can scientists test this hypothesis?

▲ **Figure 1.5** Beach mouse and inland mouse with their native habitat

Controlled Experiments In an experimental test of a hypothesis, a researcher often manipulates one component in a system and observes the effects of this change. Variables are factors that *vary* in an experiment. The factor that is manipulated by the researchers is called the **independent variable**. The measure used to judge the outcome of the experiment is called the **dependent variable**. This variable *depends* on, or is affected by, the manipulated variable. A **controlled experiment** is one in which an experimental group is compared with a control group. These groups ideally differ only in the one variable the experiment is designed to test.

Let's consider an example of a controlled experiment involving two populations of mice that belong to the same species (*Peromyscus polionotus*) but live in different environments. The beach mouse lives along the Florida seashore; the inland mouse lives on darker soil farther inland. As you can see in **Figure 1.5**, there is a striking match between mouse coloration and habitat. In 2010, biologist Hopi Hoekstra of Harvard University and a group of her students headed to Florida to test the camouflage hypothesis. They predicted that if camouflage coloration protects mice from predators, then mice that matched their environment would be preyed on less frequently than mice with coloration that did not match their habitat.

This experiment is an example of a field study, one not done in a laboratory but out in nature, using the natural habitat of the mice and their predators. The researchers built 250 plastic models of mice and painted them to resemble either beach or inland mice. Equal numbers of models were placed randomly in both habitats. The models resembling the native mice in each habitat were the control group. The mice with the non-native coloration were the experimental group. Signs of predation were recorded for three days.

As you can see by the results in **Table 1.5**, the noncamouflaged models had a much higher percentage of predation attacks in both habitats. The data thus support the camouflage hypothesis: Coloration that matches the environment protects animals from predation.

TABLE 1.5 Results from Camouflage Experiment

Habitat	Number of Attacks: On Camouflaged Models	Number of Attacks: On Noncamouflaged Models	% Attacks on Noncamouflaged Models
Beach (light habitat)	2	5	71%
Inland (dark habitat)	5	16	76%

Data from S. N. Vignieri et al., The selective advantage of crypsis in mice, *Evolution* 64: 2153–8 (2010).

TRY THIS Identify the independent and dependent variables in this experiment.

Testing Hypotheses in Humans Controlled experiments involving humans, such as tests of new medications, are called clinical trials or clinical studies. Subjects are usually randomly assigned to control and experimental groups. The control group participants are often given a placebo, a treatment (such as a sugar pill) that doesn't contain the substance being studied. In a double-blind trial, neither the researchers nor the subjects know who is in which group. Clinical trials must be cut short if preliminary results show that the treatment is either significantly harmful or significantly beneficial to the participants, because it would be unethical to knowingly harm participants or withhold effective treatment.

Observational studies are often used to test hypotheses in humans. In a retrospective study, researchers may interview people, use medical records, or examine death certificates in the attempt to identify factors that led to a specific outcome. In a prospective study, researchers enter the picture at the beginning, enrolling a group of participants, called a cohort, and then collecting data from them over a period of time. Observational studies have their limitations. A correlation between a factor and an outcome does not necessarily mean that the factor caused the outcome. Large cohort studies, however, have contributed a great deal to our understanding of the effects of many health-related factors, including diet, smoking, exercise, and environmental conditions.

? **In some studies, researchers try to match the sex, age, and general health of subjects in the control and experimental groups. What is this experimental design trying to do?**

■ Ensure that the two groups differ only in the one variable the experiment is designed to test

1.6 Hypotheses can be tested using observational data

SCIENTIFIC THINKING

Controlled experiments are not the only way to test hypotheses. Scientists often use data from observations to form and test hypotheses. Let's consider an example of how scientists have answered the question of how to classify the red panda. As you will see, the red panda story provides an excellent example of observations leading to hypotheses and the willingness of scientists to revise hypotheses to incorporate new evidence.

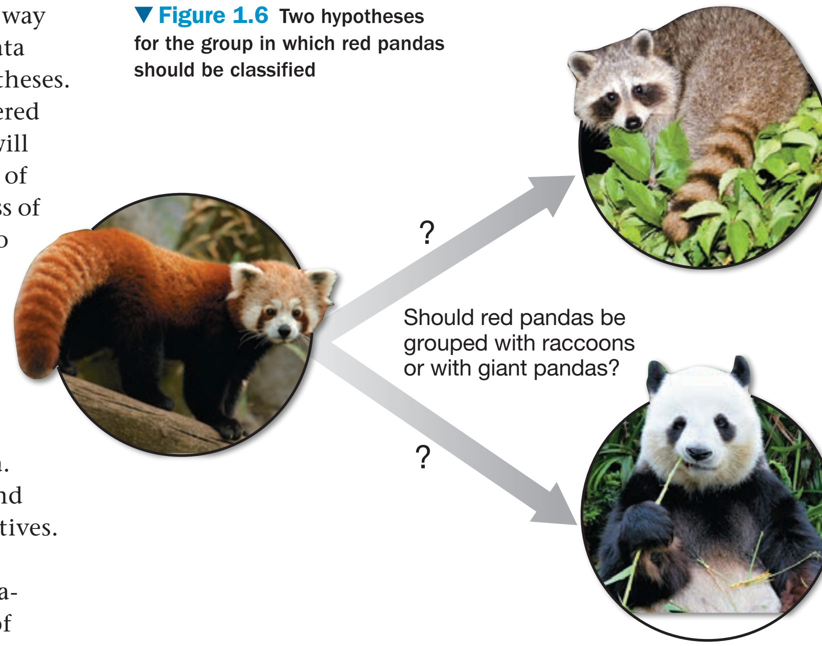
Who are the red panda's closest relatives?

From its antics in YouTube videos, the red panda might remind you of a house cat. Indeed, its scientific name, *Ailurus fulgens*, means "shining cat." But it also looks like a raccoon, and it eats bamboo and has a false thumb like a giant panda. Common names such as lesser panda, red cat-bear, and firefox reflect the confusion over the red panda's relatives. How have scientists classified this animal?

To develop hypotheses about the evolutionary relationships among species, scientists use many kinds of evidence, including comparisons of both fossils and living organisms. Based on observations of physical similarities, scientists initially hypothesized that the red panda was most closely related to raccoons, and therefore classified the two species in the same biological family **(Figure 1.6)**. Other scientists, observing that the diet and habitat of red pandas were similar to those of giant pandas, placed the two pandas together in their own family. As evidence accumulated that giant pandas are members of the bear family, it was proposed that the red panda also belonged in that family.

In recent years, scientists have increasingly used molecular evidence based on comparisons of DNA sequences to test hypotheses about evolutionary relationships. The underlying assumption is that the more closely the DNA sequences of two species match, the more closely they are related. A number of recently published molecular studies strongly support the hypothesis that red pandas are not part of either the bear or the raccoon family. As a result of this new evidence of differences in the DNA sequences of these groups, scientists now classify red pandas as the sole living species of their own family.

▼ **Figure 1.6** Two hypotheses for the group in which red pandas should be classified



? **Explain why comparisons of DNA sequences are considered observational and not experimental data.**

■ Scientists are not manipulating DNA sequences in any type of experiment but are simply recording and comparing the differences in sequences that they observe.

1.7 The process of science is repetitive, nonlinear, and collaborative

As discussed in Module 1.4, scientists use a process of inquiry that includes making observations, asking questions, forming hypotheses, and testing them. Very few scientific inquiries, however, adhere rigidly to the sequence of steps that are typically used to describe "the scientific method."

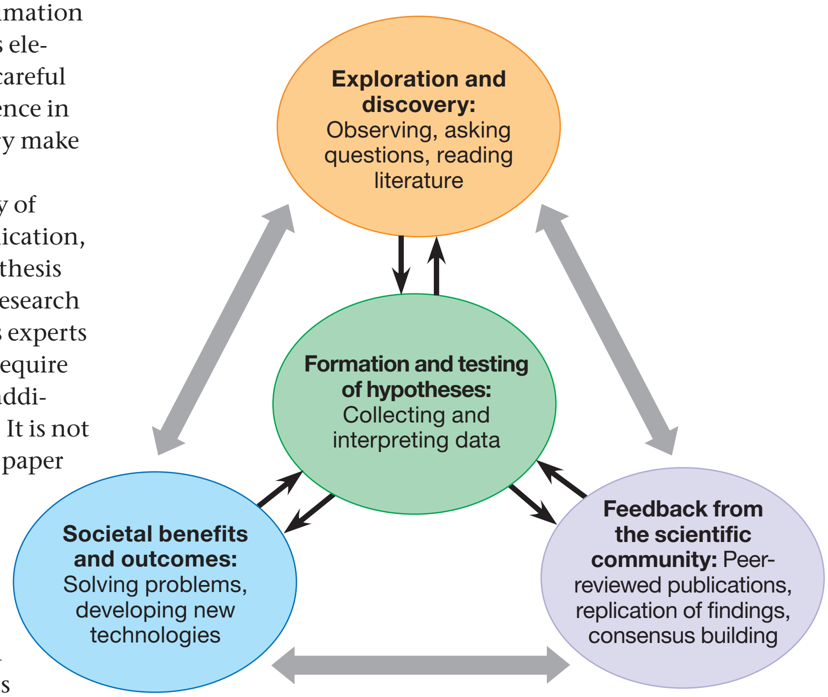
Figure 1.7, on the facing page, presents a more inclusive model of the scientific process. You can see that forming and testing hypotheses are at the center of science. This core set of activities is the reason that science does so well in explaining natural phenomena. These activities, however, are shaped by exploration and discovery (the upper circle in Figure 1.7) and influenced by interactions with other scientists and with society more generally (lower circles). The arrows pointing between the circles illustrate that the components of the scientific process interact and interconnect.

The process of science is typically repetitive and nonlinear. For example, scientists often work through several iterations of making observations and asking questions, with each round informing the next, before settling on hypotheses that they wish to test. In fine-tuning their questions, biologists rely heavily on scientific literature, the published contributions of fellow scientists—their peers. By reading about and understanding past studies, scientists can build on the foundation of existing knowledge.

Scientists rarely work alone in testing their ideas: they may learn methods from each other and share advice on experimental design and data analysis. An experimental design may need to be adjusted after initial data are collected. And results may lead to a revision of the original hypothesis or the formation of alternate ones, thus leading to further testing. In this way, scientists circle closer and closer to their best estimation of how nature works. As in all quests, science includes elements of challenge, adventure, and luck, along with careful planning, reasoning, creativity, patience, and persistence in overcoming setbacks. Such diverse elements of inquiry make science far less structured than most people realize.

Scientists share information with their community of peers through seminars, meetings, personal communication, and scientific publications. Before the results of hypothesis testing are published in a peer-reviewed journal, the research is evaluated by qualified, impartial, often anonymous experts who were not involved in the study. Reviewers often require authors to make revisions to their claims or perform additional experiments to provide more lines of evidence. It is not uncommon for a journal to "reject," or not publish, a paper if it doesn't meet the rigorous standards set by fellow scientists. When a study is published, scientists often check each other's claims by attempting to confirm observations or repeat experiments.

As indicated by the lower left circle in Figure 1.7, science is interwoven with the fabric of society. Much of scientific research is focused on particular problems that are of human concern, such as the push to cure cancer or to understand and slow the process of climate change. Societal needs often determine which research projects are funded and how extensively the results are discussed. To emphasize the connection between biology and society, each chapter of this text includes at least one Connection module. These modules also highlight the connections between biology and your own life.



▲ **Figure 1.7** A more realistic model of the process of science. This illustration in based on a model (How Science Works) from the website Understanding Science (www.understandingscience.org).

? Why is hypothesis testing at the center of the process of science?

■ Hypothesis testing is central because a core component of science is testable explanations of nature.

1.8 Biology, technology, and society are connected in important ways

CONNECTION

Many of the current issues facing society are related to biology, and they often involve our expanding technology. What are the differences between science and technology? The goal of science is to understand natural phenomena. In contrast, the goal of **technology** is to apply scientific knowledge for some specific purpose. Scientists usually speak of "discoveries," whereas engineers more often speak of "inventions." These two fields, however, are interdependent. Scientists use new technology in their research, and scientific discoveries often lead to the development of new technologies.

The potent combination of science and technology can have dramatic effects on society. For example, the discovery of the structure of DNA by Watson and Crick more than 60 years ago was aided by the technology of X-ray crystallography. Subsequent advances in DNA science have led to the technologies of DNA manipulation that today are transforming applied fields such as medicine, agriculture, and forensics.

Technology has improved our standard of living in many ways, but not without consequences. Technology has helped Earth's population to grow tenfold in the past three centuries and to more than double in just the past 40 years. There are now more than 7.3 billion people on Earth. Climate change, toxic wastes, deforestation, and increasing rates of extinction are just some of the repercussions of more and more people wielding more and more technology. Science can help identify problems and provide insight into how to slow down or prevent further damage. But solutions to these problems have as much to do with politics, economics, and cultural values as with science and technology. Every citizen has a responsibility to develop a reasonable amount of scientific literacy to be able to participate in the debates regarding science, technology, and society.

The process of science we have just explored results in new biological discoveries every day. In the next section, we introduce broad themes that you will encounter throughout your study of life.

? How do science and technology interact?

■ New scientific discoveries may lead to new technologies; new technologies may increase the ability of scientists to discover new knowledge.

Five Unifying Themes in Biology

Biology is a subject of enormous scope. Within this ever-growing body of knowledge, however, we can identify some unifying themes. In the next few modules, we'll describe the themes of evolution, information, structure and function, energy and matter, and interactions. We'll also help you recognize them as they recur throughout your study of biology.

1.9 Theme: Evolution is the core theme of biology

Life is distinguished by both its unity and its diversity. Multiple lines of evidence point to life's unity, from the similarities seen among and between fossil and living organisms, to common metabolic processes, to the universal molecule of inheritance, DNA. The amazing diversity of life is on display all around you and is documented in zoos, nature shows, and natural history museums. The scientific explanation for this unity and diversity is **evolution**, the process of change that has transformed life on Earth from its earliest forms to the vast array of organisms living today.

Darwin's Theory of Evolution The history of life, as documented by fossils and other evidence, is the saga of a changing Earth billions of years old, inhabited by an evolving cast of living forms. This evolutionary view of life came into sharp focus in November 1859, when Charles Darwin published one of the most influential books ever written, entitled *On the Origin of Species by Means of Natural Selection*.

How does Darwin's work illustrate the process of science you just learned about? As a young man, Darwin made key observations that greatly influenced his thinking. During a five-year, around-the-world voyage, he collected and documented plants, animals, and fossils in widely varying locations—from the isolated Galápagos Islands to the heights of the Andes mountains to the rain forests of Brazil. He was particularly struck by the adaptations of these varied organisms that made them well suited to their diverse habitats. After returning to England, Darwin spent more than two decades continuing his observations, performing experiments, corresponding with other scientists, and refining his thinking before he finally published his work.

The first of two main points that Darwin presented in *The Origin of Species* was that species living today arose from a succession of ancestors that were different from them. Darwin called this process "descent with modification." This insightful phrase captures both the unity of life (descent from a common ancestor) and the diversity of life (modifications that evolved as species diverged from their ancestors). **Figure 1.9A** illustrates this unity and diversity among birds. The flamingo, penguin, and hummingbird all have a common "bird" body plan of wings, beak, feet, and feathers, but these structures are highly specialized for each bird's unique lifestyle.

Darwin's second point was to propose a mechanism for evolution, which he called **natural selection**. Darwin started with two observations, from which he drew two inferences.

OBSERVATION #1: Individual variation. Individuals in a population vary in their traits, many of which seem to be heritable (passed on from parents to offspring).

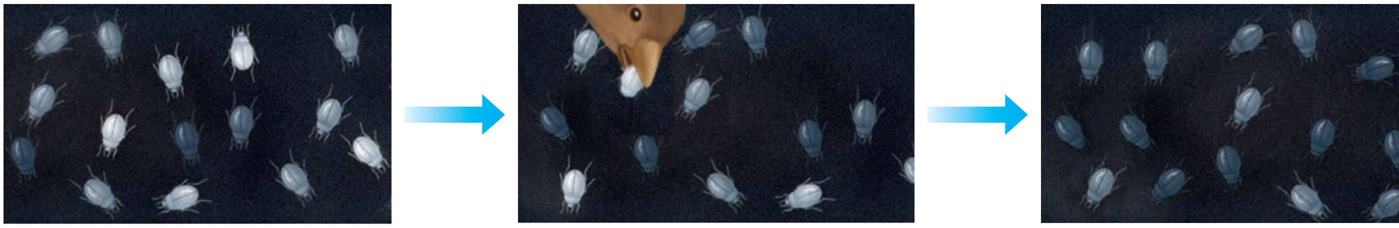
OBSERVATION #2: Overproduction of offspring. All species can produce far more offspring than the environment can support. Competition for resources is thus inevitable, and many of these offspring fail to survive and reproduce.

INFERENCE #1: Unequal reproductive success. Individuals with inherited traits best suited to the local environment are more likely to survive and reproduce than are less well-suited individuals.

INFERENCE #2: Accumulation of favorable traits over time. As a result of this unequal reproductive success over many generations, a higher and higher proportion of individuals in the population will have the advantageous traits.

▲ **Figure 1.9A** Unity and diversity among birds

TRY THIS For each bird, describe some adaptations that fit it to its environment and way of life.



▲ **Figure 1.9B** An example of natural selection in action

TRY THIS Predict what might happen if some of these beetles colonized a sand dune habitat.

Figure 1.9B uses a simple example to show how natural selection works. 1 An imaginary beetle population has colonized an area where the soil has been blackened by a recent brush fire. Initially, the population varies extensively in the inherited coloration of individuals, from very light gray to charcoal. 2 A bird eats the beetles it sees most easily, the light-colored ones. This selective predation reduces the number of light-colored beetles and favors the survival and reproductive success of the darker beetles, which pass on the genes for dark coloration to their offspring. 3 After several generations, the population is quite different from the original one. As a result of natural selection, the frequency of the darker-colored beetles in the population has increased.

Darwin realized that numerous small changes in populations as a result of natural selection could eventually lead to major alterations of species. He proposed that new species could evolve as a result of the gradual accumulation of changes over long periods of time. This could occur, for example, if one population fragmented into subpopulations isolated in different environments. In these separate arenas of natural selection, one species could gradually divide into multiple species as isolated populations adapted over many generations to different sets of environmental factors.

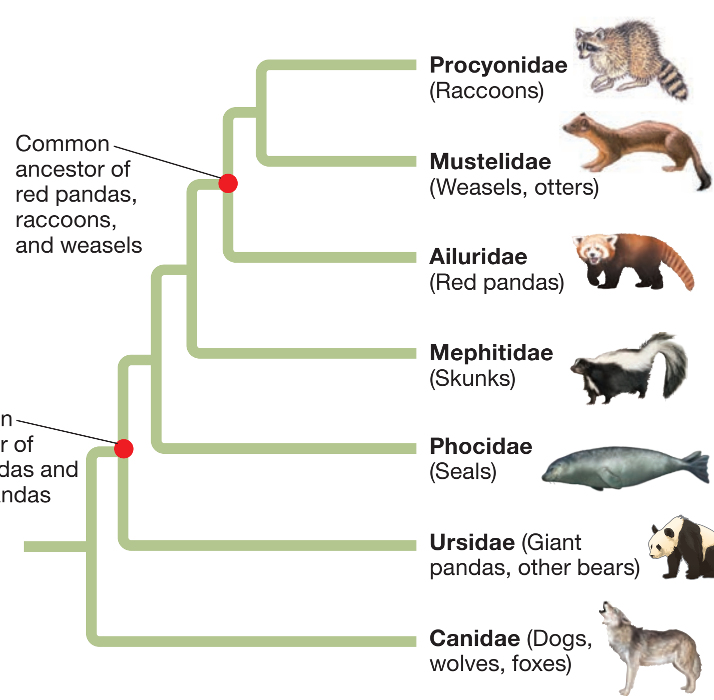
The Tree of Life Just as you have a family tree, each species on Earth today has a family history. A species represents one twig on a branching tree of life that extends back in time through ancestral species more and more remote. For example, the fossil record indicates that red pandas, raccoons, and weasels share an ancestor that existed close to 30 million years ago. Tracing back farther in time, these groups and bears share a common ancestor that lived about 40 million years ago. All mammals have hair and milk-producing mammary glands, and such similarities are what we would expect if all mammals descended from a common ancestor. Evidence indicates that the ancestral mammal arose more than 200 million years ago.

Figure 1.9C traces some of the family tree of the red panda, based on the most recent molecular evidence (see Module 1.6). Diagrams of evolutionary relationships generally take the form of branching trees, usually turned sideways and read from left to right. You can see that giant pandas, red pandas, and racoons are placed in three separate families. Red pandas are now classified as the sole living species of the family Ailuridae.

The theory of evolution by natural selection is supported by multiple lines of evidence—the fossil record, experiments, observations of natural selection in action, and ever-increasing numbers of DNA comparisons. Evolution is the central theme that makes sense of everything we know and learn about biology. Throughout this text, we'll see many more examples of both the process and products of evolution. To emphasize evolution as the central theme of biology, we include an Evolution Connection module, called out with a green icon, in each chapter.

? **Explain the cause and effect of unequal reproductive success.**

■ Those individuals with heritable traits best suited to the local environment produce the greatest number of offspring. Over many generations, the proportion of these adaptive traits increases in the population.



▲ **Figure 1.9C** An evolutionary tree of the red panda based on recent molecular data

1.10 Evolution is connected to our everyday lives

EVOLUTION CONNECTION

You just learned that natural selection is the primary mechanism of evolution, in which the environment "selects" for adaptive traits when organisms with such traits are better able to survive and reproduce. Through the selective breeding of plants and animals, humans also act as agents of evolution. As a result of **artificial selection**, our crops, livestock, and pets bear little resemblance to their wild ancestors. Humans have been modifying species for millennia by choosing which organisms reproduce, and recent advances in biotechnology have increased our capabilities. Plant biologists can now identify genes for beneficial traits in relatives of our crop plants or even in totally unrelated species, and then use genetic engineering to produce enhanced crops. For example, genes for such traits as drought tolerance, improved growth, and increased nutrition have been introduced into rice plants.

But humans also affect evolution unintentionally. The impact of habitat loss and climate change can be seen in the loss of species. Indeed, scientists estimate that the current rate of extinction is 100 to 1,000 times the typical rate seen in the fossil record. Our actions are also driving evolutionary changes in species. For example, our widespread use of antibiotics and pesticides has led to the evolution of antibiotic resistance in bacteria and pesticide resistance in insects.

How can evolutionary theory help address such worldwide problems? Understanding evolution can help us develop strategies for conservation efforts and prompt us to be more judicious in our use of antibiotics and pesticides. It can also help us create flu vaccines and HIV drugs by tracking the rapid evolution of these viruses. Identifying shared genes and studying their actions in closely related organisms may produce new knowledge about cancer or other diseases and lead to new medical treatments. Our understanding of evolution can yield many beneficial results.

? **Explain how humans are agents of both artificial selection and natural selection.**

■ We use artificial selection when choosing specific traits or genes in organisms that we breed. Our intentional and unintentional manipulations change the environment and thus affect natural selection.

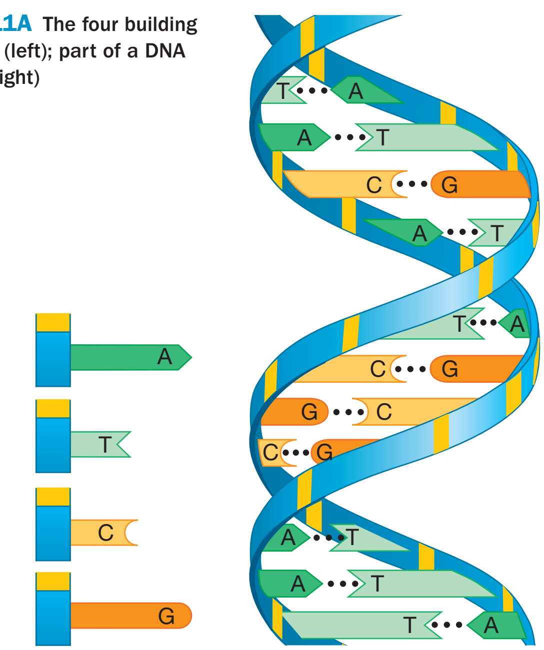
1.11 Theme: Life depends on the flow of information

The processes of life, such as reproduction, growth and development, internal regulation, and response to the environment, all depend on the transmission and use of information. Genetic information encoded in DNA determines an organism's structures and functions. But such properties also depend on the stimuli, signals, and pathways that regulate where, when, and how an organism's genetic information is expressed. Indeed, the integrated flow of genetic and other types of information is essential for life.

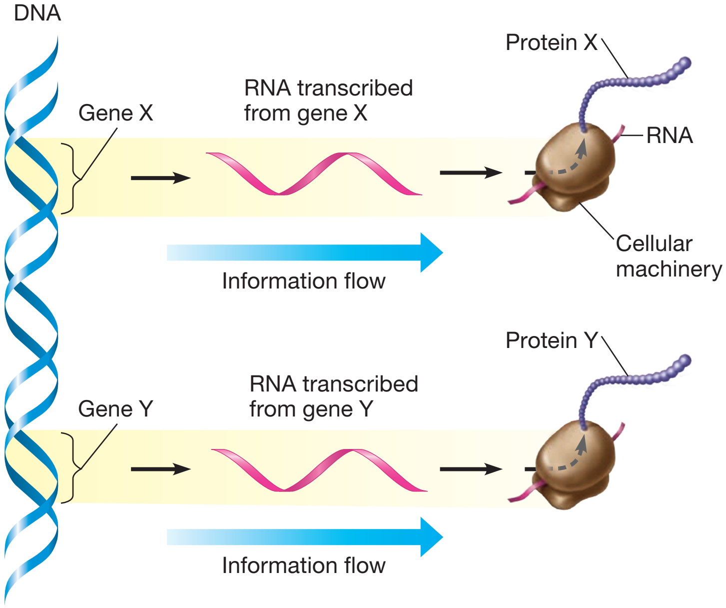
Genetic Information DNA provides the master instructions for all of a cell's functions. It is also the heritable information that is passed from one generation to the next. How does the molecular structure of DNA account for its ability to encode and transmit information? Each DNA molecule is made up of two long chains, called strands, coiled together into a double helix. The strands are made up of four kinds of chemical building blocks called nucleotides. **Figure 1.11A** (left side) illustrates these four nucleotides with different colors and letter abbreviations of their names. The right side of the figure shows a short section of a DNA double helix.

Before a cell divides, its DNA is first replicated, or copied. The two strands "unzip," and new complementary strands assemble along the separated strands—so that the information in the two resulting sets of DNA remains the same. Thus, each new cell inherits a complete set of DNA that is identical to that of the parent cell. You began as a single cell stocked with DNA inherited from your two parents. Each round of cell division transmitted copies of that DNA to what eventually became the trillions of cells in your body.

▶ **Figure 1.11A** **The four building blocks of DNA (left); part of a DNA double helix (right)**



The way DNA encodes a cell's information is analogous to the way we arrange letters of the alphabet into precise sequences with specific meanings. The word *rat*, for example, conjures up an image of a rodent; *tar* and *art*, which contain the same letters, mean very different things. We can think of the four nucleotides as the alphabet of inheritance. Specific sequences of these four chemical letters encode precise information in units of inheritance called **genes**, which are



▲ **Figure 1.11B** **The flow of information from DNA to RNA to protein**

typically hundreds or thousands of "letters" long. For most genes, the sequence provides the blueprint for making a protein, and proteins are the major players in building and maintaining the cell and carrying out its activities.

Making a protein from the instructions contained in a gene involves a sequential flow of information, which is illustrated in **Figure 1.11B**. A gene's information is first transcribed from DNA to an intermediate molecule, RNA. An RNA molecule carries the information to the protein-manufacturing machinery in the cell. There, the sequence of nucleotides in the RNA is translated into a chain of protein building blocks. Once completed, the chain forms a specific protein with a unique shape and function. This process is called **gene expression**.

All forms of life use essentially the same chemical language to translate the information stored in DNA into proteins. Called the genetic code, this universal language is a strong piece of evidence that all living organisms are related. The universal genetic code also makes it possible to engineer cells to produce proteins normally found only in some other organism. Thus, bacteria can be used to produce insulin for the treatment of diabetes by inserting a gene for human insulin into bacterial cells.

Signaling Information What Figure 1.11B does not show is that the flow of genetic information from DNA to RNA to protein is usually linked with information from the external and internal environment. For example, the information your body receives includes external stimuli such as light, sound, or chemicals, and internal stimuli such as food in your stomach or an excess of sugar in your blood. The stimulus is usually received by some type of receptor and its information is relayed within your body in the form of nervous signals, hormones, or other types of signals. This flow of information ultimately reaches individual cells and influences their behavior, often by changing the activity of existing proteins or by regulating gene expression and the production of specific proteins.

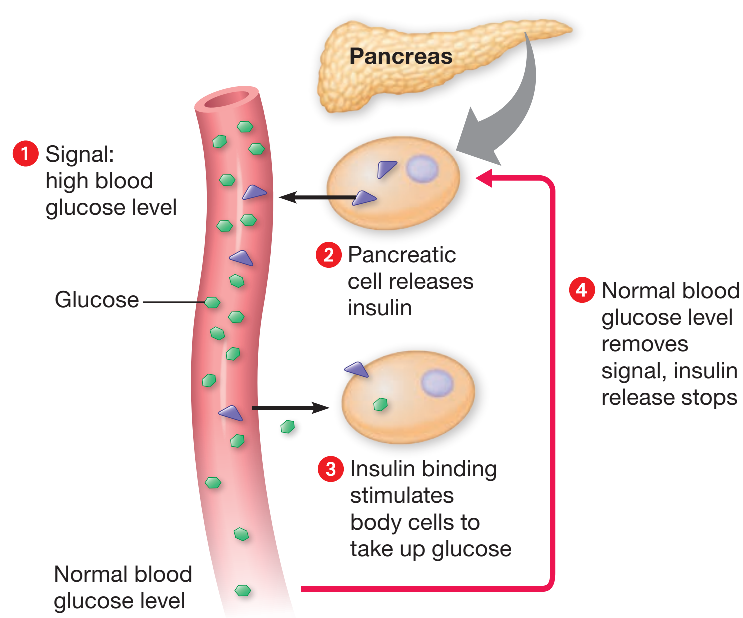
Figure 1.11C illustrates the importance of the flow of information in controlling the level of sugar in your blood. All body cells have the same genetic information, but the gene for insulin is only expressed in certain cells in your pancreas. What signals tell those cells to produce and release insulin? ❶ After a meal, the level of the sugar glucose in your blood rises. ❷ This internal signal stimulates cells in your pancreas to secrete the hormone insulin, which travels throughout your body in your blood. ❸ Insulin binds to receptors on body cells, causing them to take up glucose. ❹ The now-lowered blood glucose level removes the signal, and insulin secretion decreases. Information flow through such regulatory systems enables organisms to maintain relatively stable and beneficial internal conditions.

Receiving and relaying information is evident at all levels of biological organization. The plaque that forms on your teeth is made up of bacteria, which exchange signals that influence their growth and community organization. Cells in a developing embryo exchange and respond to signals that affect their gene expression and ultimately lead to a highly organized body form. Organisms depend on information to maintain favorable internal conditions in response to environmental changes. The flow of information within and between organisms is central to the structure and functioning of all communities.

Throughout this text, you'll find many more examples of the flow of information. Some of these examples will be highlighted by this icon: **INFORMATION**.

? **How is signaling information involved in the expression of genetic information?**

Information from the internal and external environment affects gene expression—where and when particular genes are activated and proteins made.



▲ **Figure 1.11C** **The flow of information in the regulation of the level of glucose in the blood**

TRY THIS **Describe the action of insulin as a signaling molecule in this regulatory pathway.**

1.12 Theme: Structure and function are related

A third theme that pervades all of biology is the correlation of structure and function. When considering useful objects around your home, you may note that form generally fits function. A screwdriver tightens or loosens screws, a hammer pounds nails. Because of their form, these tools can't do each other's jobs. You use a spoon to eat soup, but if you are spearing a piece of meat, you use a fork. Similarly, in biological systems, structure (the shape of something) and function (what it does) are almost always related, with each providing insight into the other.

The relationship between structure and function can be observed at every level of life. At the molecular level, the structure of a protein correlates with its function, whether it is part of the strong ligaments holding your bones together or the hemoglobin molecules transporting oxygen in your blood. On the cellular level, the long extensions of nerve cells enable them to transmit impulses from your spinal cord to your toes. The long, thin cells of fungi enable them to extend through their food source and absorb nutrients. The thick walls surrounding plant cells provide structural support to the plant leaf pictured in **Figure 1.12A**, just as the tough exoskeleton of the beetle supports its body.

Let's consider the red panda's hand as another example. In **Figure 1.12B**, you can see a red panda holding some bamboo. Scientists using an X-ray technique known as computed tomography (CT) produced a scan of the hand and wrist of a red panda (upper left part of the figure) to highlight the small bone protruding from the wrist, called the radial sesamoid. In red pandas, this bone is much larger than in related animals and is often referred to as a "false thumb." What might be its function? Just as your thumbs are useful in grasping objects, the red panda's wrist projection helps it grasp bamboo. By studying the fossil record, scientists propose that this projection originally evolved in the red panda's carnivorous ancestor as an adaptation that enabled it to move along branches in trees. Secondarily, this projection enabled the plant-eating red panda to hold on to bamboo. In the evolutionary history of life, we will encounter many examples of the remodeling of existing structures to new functions.

▲ **Figure 1.12B** A red panda grasping bamboo; a CT scan showing the "false thumb" of a red panda (inset)

▲ **Figure 1.12A** Structural adaptations in the form of plant cell walls and insect exoskeletons that function in physical support

Interestingly, the giant panda also has a "false thumb," yet much larger. As discussed in Module 1.6, this shared "panda thumb" and bamboo diet once led biologists to classify the red panda and the giant panda as close relatives. However, evidence from fossils and comparisons of DNA indicate that these similar structural adaptations evolved separately in the two distinct lineages.

The close match of form and function in the structures of life can be explained by natural selection. The organisms whose structures best performed their functions would have been most likely to have reproductive success, thereby passing those adaptations on to their offspring. Given that existing structures are often remodeled for new functions, however, we don't expect evolutionary adaptations to be perfect (see the introduction to Chapter 20).

Throughout the text we will see how the theme of structure and function applies to life at all levels of organization, from molecules and cells, to the internal organization of plants and animals, to whole ecosystems. To help you recognize this theme, specific examples will be highlighted with this icon: **STRUCTURE AND FUNCTION**.

? Look at the structure of your hand and explain how its structure supports its function.

■ The finger joints and opposable digits allow you to manipulate objects.

1.13 Theme: Life depends on the transfer and transformation of energy and matter

The activities of life—movement, growth, reproduction, regulation, and most cellular processes—require energy. The input of energy, primarily from the sun, and the conversion of energy from one form to another make life possible. **Figure 1.13** is a simplified diagram of the transfer and transformations of energy and matter taking place in a forest in Canada. Plants are the producers that provide the food for a typical terrestrial ecosystem. A tree, for example, absorbs water (H_2O) and minerals through its roots, and its leaves take in carbon dioxide (CO_2) from the air. In the process of photosynthesis, energy from sunlight is stored as chemical energy as the atoms in CO_2 and H_2O are rearranged into sugar molecules that are rich in chemical energy.

The consumers in an ecosystem eat plants and other animals. The moose in Figure 1.13 eats the grasses and tender shoots and leaves of trees in the forest ecosystem. To release the chemical energy in food, animals (as well as plants and most other organisms) use the process of cellular respiration, taking in O_2 from the air and releasing CO_2. Consumers use both the energy and the atoms (matter) obtained from food to build new molecules. For example, proteins in the moose's fur were assembled from atoms that were once in its food. An animal's wastes return matter to the environment.

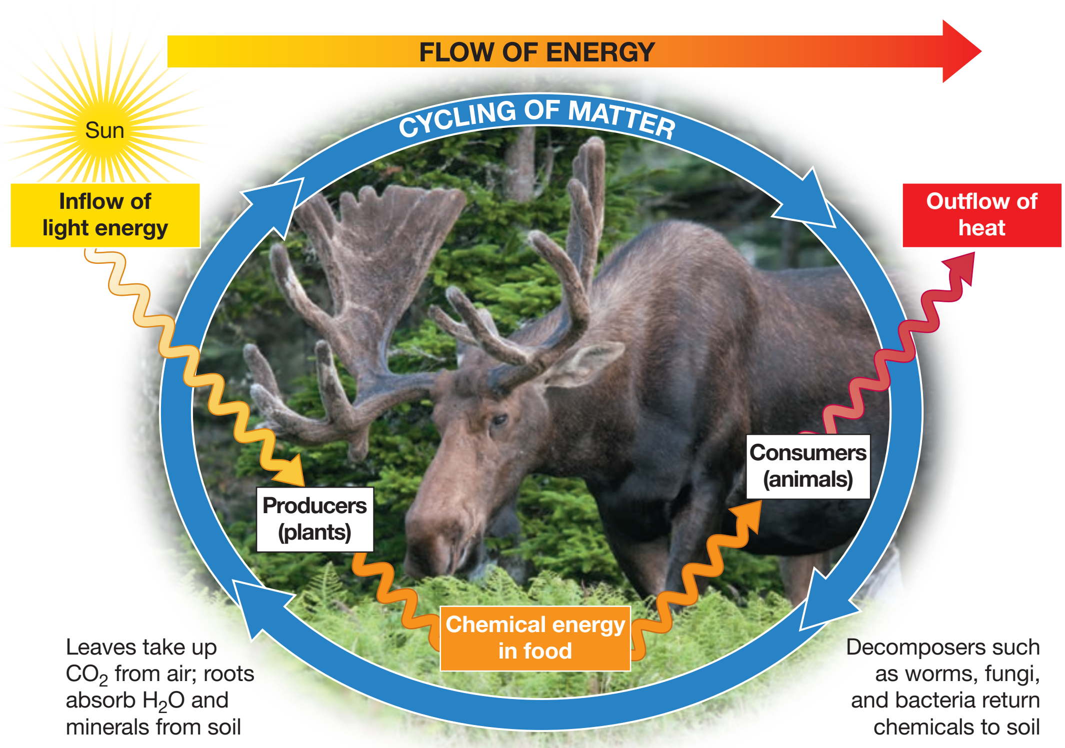
Vital parts of this ecosystem are the small animals, fungi, and bacteria in the soil that decompose wastes and the remains of dead organisms. These decomposers act as recyclers, changing complex matter into simpler chemicals that return to the environment and are once again available to producers.

As illustrated in Figure 1.13, the dynamics of ecosystems can be summarized with two major processes—the flow of energy and the cycling of matter. An ecosystem gains and loses energy constantly. Energy flows into most ecosystems as sunlight (yellow arrow), and photosynthetic organisms convert it into the chemical energy in sugars and other energy-rich molecules. Chemical energy in food (orange arrow) is then passed through a series of consumers and, eventually, to decomposers, powering each organism in turn. In the process of these energy conversions between and within organisms, some energy is always converted to heat, which is then lost from the ecosystem (red arrow). Thus, energy flows through an ecosystem in one direction, entering as light and exiting as heat. By contrast, matter cycles within an ecosystem, from the air and soil to producers, to consumers and decomposers, and back to the air and soil (shown by the blue arrows in the figure).

This "chemical square dance" in which molecules swap chemical partners as they receive, convert, and release energy is never-ending in all forms of life. Throughout your study of biology, you will see many examples of this theme, from microscopic cellular processes to ecosystem-wide cycles of carbon and other nutrients. To help you recognize this theme, some examples will be highlighted with this icon: **ENERGY AND MATTER**.

? **Describe how photosynthesis transforms energy and matter.**

Using the energy of sunlight, CO_2 and H_2O (matter) are converted into sugar molecules with stored chemical energy.



▲ **Figure 1.13** The flow of energy and cycling of matter in an ecosystem

1.14 Theme: Life depends on interactions within and between systems

As you saw in Module 1.3, the study of life extends from the microscopic scale of the molecules and cells that make up an organism to the global scale of the entire living planet. Working our way upward through this hierarchy, we noted that novel properties arise at each higher level. Such emergent properties represent an important concept in biology. The familiar saying that "the whole is greater than the sum of its parts" captures this idea. The emergent properties of each level result from the specific arrangement and interactions of its parts. Such a combination of components forms a more complex organization called a *system*. Biological systems can range from the molecular machinery of a cell to the functioning of an ecosystem or the entire biosphere.

Your body is a system, and it is the interactions between the parts (molecules, cells, tissues, organs) that allow you to maintain a relatively stable internal environment. Interactions and connections between your circulatory, digestive, and endocrine (hormonal) systems—your blood, pancreatic cells, molecules of insulin, and body cells—enable the regulation of blood glucose level (see Figure 1.11C). An alteration in one of the components of such a system disrupts its functioning and can lead to disease. For example, type 1 diabetes is the result of pancreatic cells no longer producing insulin; type 2 diabetes develops when body cells no longer respond to insulin.

Using an approach called **systems biology**, scientists attempt to model the behavior of biological systems by analyzing the interactions among their parts. For example, researchers have produced a complex systems map of the interactions among 2,346 proteins in a fruit fly cell, based on a huge database of known proteins and their actions. One goal of developing such models is to be able to predict how a change in one component will affect the other parts of the system. Thus the systems map of fruit fly proteins might show how an increase in the activity of a certain protein can ripple through a cell's molecular circuitry to affect other proteins and functions of the cell.

Recent technological advances have enabled scientists to pose new kinds of questions about system interactions at the molecular level. Faster and less expensive sequencing techniques have greatly increased the rate at which the nucleotide sequences in DNA can be determined. New computational tools are being used to store, organize, and analyze this huge volume of data. Scientists can now study and compare whole sets of genes and proteins in a species and across multiple species, asking questions about the functions of individual genes as well as the interactions among their protein products. These molecular techniques have also enabled the identification of organisms that were previously unknown, ranging from the communities of bacteria living in our bodies to the vast array of microorganisms that play essential roles in every ecosystem.

Systems biology often involves interdisciplinary research as well as mathematical or computer modeling of the dynamic behavior of an integrated network of components. Thus, scientists can study and predict the effects of climate change by modeling increases in atmospheric levels of CO_2 and global warming, monitoring weather patterns, and investigating impacts on individual populations as well as the diversity of biological communities.

▲ **Figure 1.14** Interactions among some of the components of an ecosystem

TRY THIS Identify the interconnections and interactions of the abiotic and biotic components illustrated in this photograph.

Life is characterized by interconnections and interactions. Consider the sloth in **Figure 1.14**. This denizen of South American rain forests is sporting a luxuriant growth of photosynthetic bacteria (the greenish tinge in its hair). The sloth depends on trees for food and shelter; the tree uses nutrients from the decomposition of the sloth's feces; the bacteria gain access to the sunlight necessary for photosynthesis by living on the sloth; and the sloth is camouflaged from predators by its greenish-brown coat. We can find these types of interactions among component parts at every level of biological organization. To help you recognize the theme of system interactions and interconnections in this text, some examples will be identified with this icon: **INTERACTIONS**.

As you embark on your study of biology, watch for the five themes: evolution, information, structure and function, energy and matter, and interactions. These unifying themes can provide a framework to help you organize your growing biological knowledge. And remember how this knowledge came to be in the first place: through the exciting and rewarding process of science.

? **A box of bicycle parts won't do anything, but if the parts are properly assembled, you can take a ride. What does this illustrate?**

■ Emergent properties of the interacting components of a system

CHAPTER 1 REVIEW

For practice quizzes, BioFlix animations, MP3 tutorials, video tutors, and more study tools designed for this textbook, go to MasteringBiology™

REVIEWING THE CONCEPTS

Biology: The Scientific Study of Life (1.1–1.3)

1.1 What is life? Biology is the scientific study of life. Properties of life include order, reproduction, growth and development, energy processing, regulation, response to the environment, and evolutionary adaptation. The cell is the structural and functional unit of life.

1.2 Biologists arrange the diversity of life into three domains. Taxonomists name species and classify them into broader groups. Domains Bacteria and Archaea contain organisms with simple cells. Domain Eukarya includes various protists and the kingdoms Fungi, Plantae, and Animalia.

1.3 In life's hierarchy of organization, new properties emerge at each level. Biological organization unfolds as follows: biosphere > ecosystem > community > population > organism > organ system > organ > tissue > cell > organelle > molecule. Emergent properties result from the interactions among component parts.

The Process of Science (1.4–1.8)

1.4 What is science? Science uses an evidence-based process of inquiry to investigate the natural world. The scientific approach involves observations, hypotheses, predictions, tests of hypotheses via experiments or additional observations, and analysis of data. A scientific theory is broad in scope and supported by a large body of evidence.

1.5 Hypotheses can be tested using controlled experiments. The use of control and experimental groups can demonstrate the effect of a single variable. Hypotheses can be tested in humans with clinical trials, as well as retrospective or prospective observational studies.

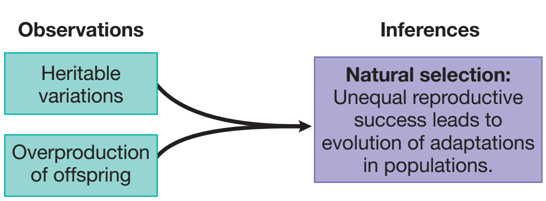
1.6 Hypotheses can be tested using observational data. Scientists tested hypotheses about the evolutionary relationships of red pandas. Recent studies comparing DNA sequences classify the red panda as the only living species in its family.

1.7 The process of science is repetitive, nonlinear, and collaborative. Forming and testing hypotheses is at the core of science. This endeavor is influenced by three spheres: exploration and discovery; analysis and feedback from the scientific community; and societal benefits and outcomes.

1.8 Biology, technology, and society are connected in important ways. Technological advances stem from scientific research, and research benefits from new technologies.

Five Unifying Themes in Biology (1.9–1.14)

1.9 Theme: Evolution is the core theme of biology. Darwin synthesized the theory of evolution by natural selection.

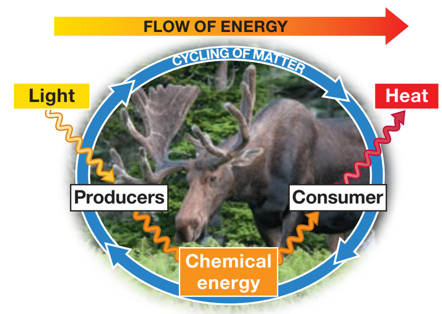


1.10 Evolution is connected to our everyday lives. Evolutionary theory is useful in medicine, agriculture, and conservation. Human-caused environmental changes are powerful selective forces that affect the evolution of many species.

1.11 Theme: Life depends on the flow of information. DNA is responsible for heredity and for programming the activities of a cell by providing the blueprint for proteins. Information from the external and internal environment includes the stimuli, signals, and pathways that regulate body processes and gene expression.

1.12 Theme: Structure and function are related. Structure is related to function at all levels of organization.

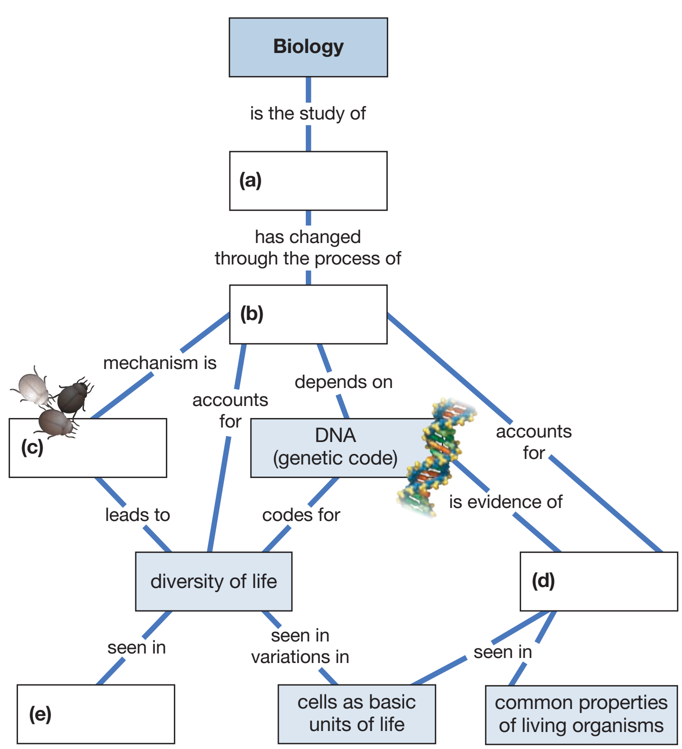
1.13 Theme: Life depends on the transfer and transformation of energy and matter. Energy flows through an ecosystem in one direction—entering as sunlight, converted to chemical energy by producers, passed on to consumers, and exiting as heat. Ecosystems are characterized by the cycling of matter from the atmosphere and soil through producers, consumers, decomposers, and back to the environment.



1.14 Theme: Life depends on interactions within and between systems. Emergent properties are the result of interactions between the components of a system. Systems biology models the complex behavior of biological systems.

CONNECTING THE CONCEPTS

1. Complete the following map organizing one of biology's major themes.



TESTING YOUR KNOWLEDGE

Level 1: Knowledge/Comprehension

2. All the organisms on your campus make up
   a. an ecosystem.
   b. a community.
   c. a population.
   d. the biosphere.
3. Which of these is *not* a property of all living organisms?
   a. capable of reproduction
   b. uses energy
   c. composed of multiple cells
   d. responds to the environment
4. Which of the following statements best distinguishes hypotheses from theories in science?
   a. Theories are hypotheses that have been proven.
   b. Hypotheses usually are narrow in scope; theories have broad explanatory power.
   c. Hypotheses are tentative guesses; theories are correct answers to questions about nature.
   d. Hypotheses and theories are different terms for essentially the same thing in science.
5. Which of the following best demonstrates the unity among all living organisms?
   a. structure correlated with function
   b. DNA and a common genetic code
   c. emergent properties
   d. natural selection
6. A controlled experiment is one that
   a. proceeds slowly enough that a scientist can make careful records of the results.
   b. keeps all variables constant.
   c. is repeated many times to make sure the results are accurate.
   d. tests experimental and control groups in parallel.
7. Which of the following is a *true* statement of observational data?
   a. It is always qualitative, not quantitative.
   b. It is used to form hypotheses, but not to test them.
   c. It can include comparisons of fossils as well as DNA sequences.
   d. It is the type of data used for the independent variable in a controlled experiment.

Level 2: Application/Analysis

8. A biologist studying interactions among the bacteria in an ecosystem could *not* be working at which level in life's hierarchy? (*Choose carefully and explain your answer.*)
   a. the population level
   b. the molecular level
   c. the organism level
   d. the organ level
9. Which of the following best describes the logic of scientific inquiry?
   a. If I generate a testable hypothesis, my experiments will support it.
   b. If my prediction is correct, it will lead to a testable hypothesis.
   c. If my observations are accurate, they will support my hypothesis.
   d. If my hypothesis is correct, I can expect certain test results.
10. In an ecosystem, how is the flow of energy similar to that of matter, and how is it different?
11. Explain the role of heritable variations in Darwin's theory of natural selection.
12. Describe the process of scientific inquiry and explain why it is not a rigid method.
13. Contrast technology with science. Give an example of each to illustrate the difference.

Level 3: Synthesis/Evaluation

14. Biology can be described as having both a vertical scale and a horizontal scale. Explain what that means.
15. Explain what is meant by this statement: Natural selection is an editing mechanism rather than a creative process.
16. The graph below shows the results of an experiment in which mice learned to run through a maze.

   a. State the hypothesis and prediction that you think this experiment tested.
   b. Which was the control group and which the experimental? Why was a control group needed?
   c. List some variables that must have been controlled so as not to affect the results.
   d. Do the data support the hypothesis? Explain.
17. **SCIENTIFIC THINKING** Suppose that in an experiment similar to the camouflage experiment described in Module 1.5, a researcher observed and recorded more total predator attacks on dark-model mice in the inland habitat than on dark models in the beach habitat. From comparing these two pieces of data, the researcher concluded that the camouflage hypothesis is false. Do you think this conclusion is justified? Why or why not?
18. The fruits of wild species of tomato are tiny compared with the giant beefsteak tomatoes available today. This difference in fruit size is almost entirely due to the larger number of cells in the domesticated fruits. Plant biologists have recently discovered genes that are responsible for controlling cell division in tomatoes. Why would such a discovery be important to producers of other kinds of fruits and vegetables? To the study of human development and disease? To our basic understanding of biology?
19. The news media and popular magazines frequently report stories that are connected to biology. In the next 24 hours, record the ones you hear or read about in three different sources and briefly describe the biological connections in each story.

Answers to all questions can be found in Appendix 4.