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Introduction: Themes in the Study of Life



▲ Figure 1.1 How is the mother-of-pearl plant adapted to its environment?

KEY CONCEPTS

- 1.1 The themes of this book make connections across different areas of biology
- 1.2 The Core Theme: Evolution accounts for the unity and diversity of life
- 1.3 In studying nature, scientists make observations and then form and test hypotheses
- 1.4 Science benefits from a cooperative approach and diverse viewpoints

OVERVIEW

Inquiring About Life

The mother-of-pearl plant, or ghost plant (Figure 1.1 and cover), is native to a single mountain in northeastern Mexico. Its fleshy, succulent leaves and other features allow this plant to store and conserve water. Even when rain falls, the plant's access to water is limited because it grows in crevices

of vertical rock walls, where little soil is present to hold rainwater (Figure 1.2). The plant's water-conserving characteristics help it survive and thrive in these nooks and crannies. Similar features are found in many plants that live in dry environments, allowing them to eke out a living where rain is unpredictable.

An organism's adaptations to its environment, such as adaptations for conserving water, are the result of **evolution**, the process of change that has transformed life on Earth from its earliest beginnings to the diversity of organisms living today. Evolution is the fundamental organizing principle of biology and the core theme of this book.

Although biologists know a great deal about life on Earth, many mysteries remain. For instance, what exactly led to the origin of flowering among plants such as the one pictured here? Posing questions about the living world and seeking science-based answers—scientific inquiry—are the central activities of **biology**, the scientific study of life. Biologists' questions can be ambitious. They may ask how a single tiny cell becomes a tree or a dog, how the human mind works, or how the different forms of life in a forest interact. Most people wonder about the organisms living around them, and many interesting questions probably occur to you when you are out-of-doors, surrounded by the natural world. When they do, you are already thinking like a biologist. More than anything else, biology is a quest, an ongoing inquiry about the nature of life.

What is life? Even a small child realizes that a dog or a plant is alive, while a rock or a lawn mower is not. Yet the phenomenon we call life defies a simple, one-sentence definition. We recognize life by what living things do. Figure 1.3, on the next page, highlights some of the properties and processes we associate with life.

While limited to a handful of images, Figure 1.3 reminds us that the living world is wondrously varied. How do biologists



▲ Figure 1.2 The mother-of-pearl plant (*Graptopetalum paraguayense*). This plant's thick leaves hold water, enabling it to live where soil is scarce. The leaves vary in color, as seen here.

▼ **Order.** This close-up of a sunflower illustrates the highly ordered structure that characterizes life.



▲ **Regulation.** The regulation of blood flow through the blood vessels of this jackrabbit's ears helps maintain a constant body temperature by adjusting heat exchange with the surrounding air.



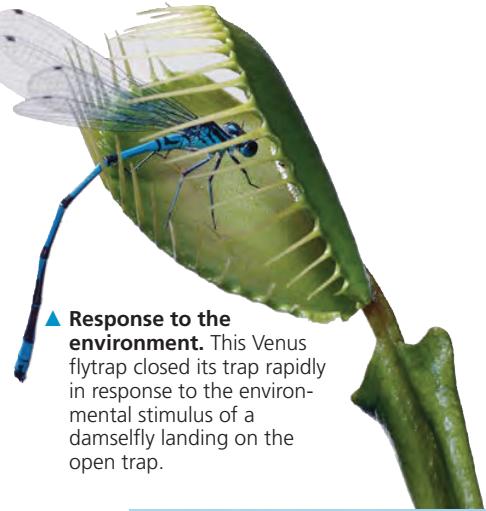
▲ **Energy processing.** This hummingbird obtains fuel in the form of nectar from flowers. The hummingbird will use chemical energy stored in its food to power flight and other work.

▲ **Figure 1.3** Some properties of life.

make sense of this diversity and complexity? This opening chapter sets up a framework for answering this question. The first part of the chapter provides a panoramic view of the biological “landscape,” organized around some unifying themes. We then focus on biology’s core theme, evolution, with an introduction to the reasoning that led Charles Darwin to his explanatory theory. Next, we look at scientific inquiry—how scientists raise and attempt to answer questions about the natural world. Finally, we address the culture of science and its effects on society.



▲ **Evolutionary adaptation.** The appearance of this pygmy sea horse camouflages the animal in its environment. Such adaptations evolve over many generations by the reproductive success of those individuals with heritable traits that are best suited to their environments.



▲ **Response to the environment.** This Venus flytrap closed its trap rapidly in response to the environmental stimulus of a damselfly landing on the open trap.



► **Reproduction.** Organisms (living things) reproduce their own kind. Here, a baby giraffe stands close to its mother.



▲ **Growth and development.** Inherited information carried by genes controls the pattern of growth and development of organisms, such as this Nile crocodile.

CONCEPT 1.1

The themes of this book make connections across different areas of biology

Biology is a subject of enormous scope, and news reports reveal exciting new biological discoveries being made every day. Simply memorizing the factual details of this huge subject is most likely not the best way to develop a coherent view of

life. A better approach is to take a more active role by connecting the many things you learn to a set of themes that pervade all of biology. Focusing on a few big ideas—ways of thinking about life that will still hold true decades from now—will help you organize and make sense of all the information you'll encounter as you study biology. To help you, we have selected eight unifying themes to serve as touchstones as you proceed through this book.

Theme: New Properties Emerge at Each Level in the Biological Hierarchy

The study of life extends from the microscopic scale of the molecules and cells that make up organisms to the global scale of the entire living planet. We can divide this enormous range into different levels of biological organization.

Imagine zooming in from space to take a closer and closer look at life on Earth. It is spring in Ontario, Canada, and our destination is a local forest, where we will eventually explore a maple leaf right down to the molecular level. **Figure 1.4**, on the next two pages, narrates this journey into life, with the numbers leading you through the levels of biological organization illustrated by the photographs.

Emergent Properties

If we now zoom back out from the molecular level in Figure 1.4, we can see that novel properties emerge at each step, properties that are not present at the preceding level. These **emergent properties** are due to the arrangement and interactions of parts as complexity increases. For example, although photosynthesis occurs in an intact chloroplast, it will not take place in a disorganized test-tube mixture of chlorophyll and other chloroplast molecules. Photosynthesis requires a specific organization of these molecules in the chloroplast. To take another example, if a blow to the head disrupts the intricate architecture of a human brain, the mind may cease to function properly even though all of the brain tissues are still present. Our thoughts and memories are emergent properties of a complex network of nerve cells. At a much higher level of biological organization—at the ecosystem level—the recycling of chemical elements essential to life, such as carbon, depends on a network of diverse organisms interacting with each other and with the soil, water, and air.

Emergent properties are not unique to life. A box of bicycle parts won't take you anywhere, but if they are arranged in a certain way, you can pedal to your chosen destination. And while the graphite in a pencil "lead" and the diamond in a wedding ring are both pure carbon, they have very different appearances and properties due to the different arrangements of their carbon atoms. Both of these examples point out the importance of arrangement. Compared to such nonliving examples, however, the unrivaled complexity of biological systems makes the emergent properties of life especially challenging to study.

The Power and Limitations of Reductionism

Because the properties of life emerge from complex organization, scientists seeking to understand biological systems confront a dilemma. On the one hand, we cannot fully explain a higher level of order by breaking it down into its parts. A dissected animal no longer functions; a cell reduced to its chemical ingredients is no longer a cell. Disrupting a living system interferes with its functioning. On the other hand, something as complex as an organism or a cell cannot be analyzed without taking it apart.

Reductionism—the approach of reducing complex systems to simpler components that are more manageable to study—is a powerful strategy in biology. For example, by studying the molecular structure of DNA that had been extracted from cells, James Watson and Francis Crick inferred, in 1953, how this molecule could serve as the chemical basis of inheritance. The central role of DNA in cells and organisms became better understood, however, when scientists were able to study the interactions of DNA with other molecules. Biologists must balance the reductionist strategy with the larger-scale, holistic objective of understanding emergent properties—how the parts of cells, organisms, and higher levels of order, such as ecosystems, work together. This is the goal of an approach developed over the last 50 years called systems biology.

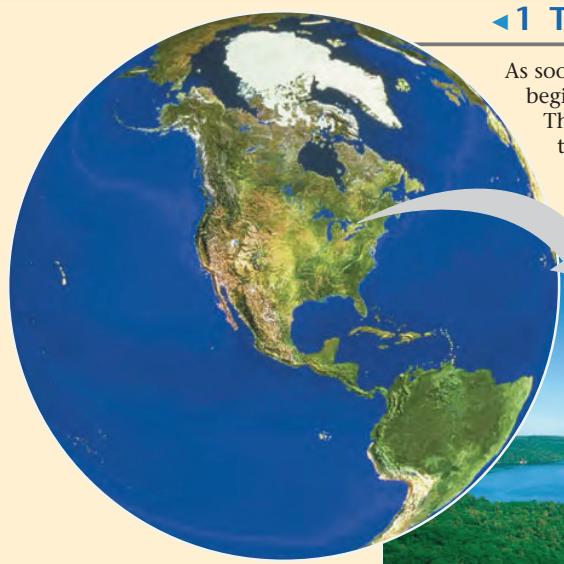
Systems Biology

A system is simply a combination of components that function together. A biologist can study a system at any level of organization. A single leaf cell can be considered a system, as can a frog, an ant colony, or a desert ecosystem. To understand how such systems work, it is not enough to have a "parts list," even a complete one. Realizing this, many researchers are now complementing the reductionist approach with new strategies for studying whole systems. This change in perspective is analogous to moving from ground level on a street corner, where you can observe local traffic, to a helicopter high above a city, from which you can see how variables such as time of day, construction projects, accidents, and traffic-signal malfunctions affect traffic throughout the city.

Systems biology is an approach that attempts to model the dynamic behavior of whole biological systems based on a study of the interactions among the system's parts. Successful models enable biologists to predict how a change in one or more variables will affect other components and the whole system. Thus, the systems approach enables us to pose new kinds of questions. How might a drug that lowers blood pressure affect the functioning of organs throughout the human body? How might increasing a crop's water supply affect processes in the plants, such as the storage of molecules essential for human nutrition? How might a gradual increase in atmospheric carbon dioxide alter ecosystems and the entire biosphere? The ultimate aim of systems biology is to answer large-scale questions like the last one.

▼ Figure 1.4

Exploring Levels of Biological Organization



◀ 1 The Biosphere

As soon as we are near enough to Earth to make out its continents and oceans, we begin to see signs of life—in the green mosaic of the planet's forests, for example. This is our first view of the biosphere, which consists of all life on Earth and all the places where life exists—most regions of land, most bodies of water, the atmosphere to an altitude of several kilometers, and even sediments far below the ocean floor and rocks many kilometers below Earth's surface.

◀ 2 Ecosystems

As we approach Earth's surface for an imaginary landing in Ontario, we can begin to make out a forest with an abundance of trees that lose their leaves in one season and grow new ones in another (deciduous trees). Such a deciduous forest is an example of an ecosystem. Grasslands, deserts, and the ocean's coral reefs are other types of ecosystems. An ecosystem consists of all the living things in a particular area, along with all the nonliving components of the environment with which life interacts, such as soil, water, atmospheric gases, and light. All of Earth's ecosystems combined make up the biosphere.

▶ 3 Communities

The entire array of organisms inhabiting a particular ecosystem is called a biological community. The community in our forest ecosystem includes many kinds of trees and other plants, a diversity of animals, various mushrooms and other fungi, and enormous numbers of diverse microorganisms, which are living forms, such as bacteria, that are too small to see without a microscope. Each of these forms of life is called a *species*.



▶ 4 Populations

A population consists of all the individuals of a species living within the bounds of a specified area. For example, our Ontario forest includes a population of sugar maple trees and a population of white-tailed deer. We can now refine our definition of a community as the set of populations that inhabit a particular area.

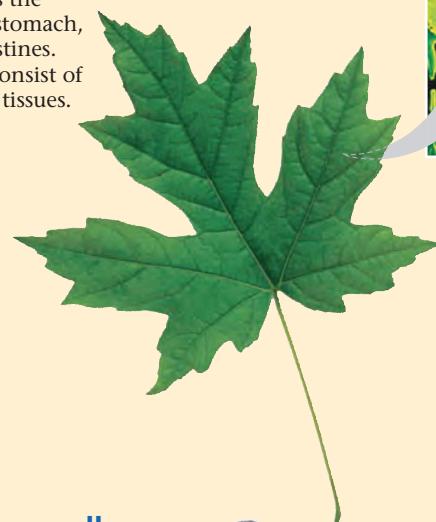


◀ 5 Organisms

Individual living things are called organisms. Each of the maple trees and other plants in the forest is an organism, and so is each forest animal—whether deer, squirrel, frog, or beetle. The soil teems with microorganisms such as bacteria.

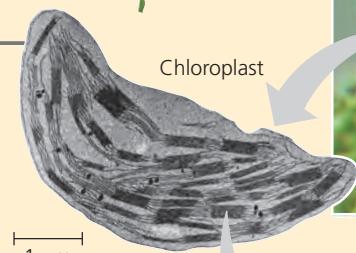
▼6 Organs and Organ Systems

The structural hierarchy of life continues to unfold as we explore the architecture of the more complex organisms. A maple leaf is an example of an organ, a body part that carries out a particular function in the body. Stems and roots are the other major organs of plants. Examples of human organs are the brain, heart, and kidney. The organs of humans, other complex animals, and plants are organized into organ systems, each a team of organs that cooperate in a larger function. For example, the human digestive system includes such organs as the tongue, stomach, and intestines. Organs consist of multiple tissues.



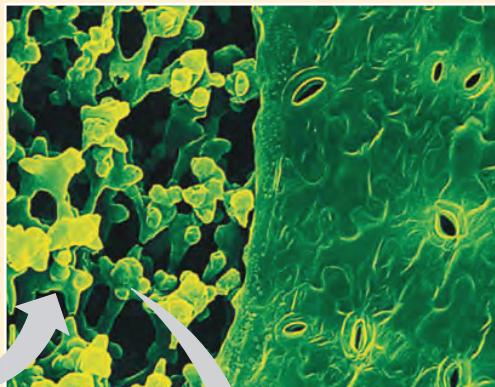
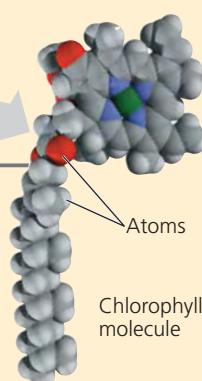
►9 Organelles

Chloroplasts are examples of organelles, the various functional components present in cells. In this image, a very powerful tool called an electron microscope brings a single chloroplast into sharp focus.



►10 Molecules

Our last scale change drops us into a chloroplast for a view of life at the molecular level. A molecule is a chemical structure consisting of two or more small chemical units called atoms, which are represented as balls in this computer graphic of a chlorophyll molecule. Chlorophyll is the pigment molecule that makes a maple leaf green. One of the most important molecules on Earth, chlorophyll absorbs sunlight during the first step of photosynthesis. Within each chloroplast, millions of chlorophyll molecules, together with accessory molecules, are organized into the equipment that converts light energy to the chemical energy of food.



◀7 Tissues

Our next scale change—to see the tissues of a leaf—requires a microscope. Each tissue is made up of a group of cells that work together, performing a specialized function. The leaf shown here has been cut on an angle. The honeycombed tissue in the interior of the leaf (left portion of photo) is the main location of photosynthesis, the process that converts light energy to the chemical energy of sugar and other food. We are viewing the sliced leaf from a perspective that also enables us to see the jigsaw puzzle-like “skin” on the surface of the leaf, a tissue called epidermis (right part of photo). The pores through the epidermis allow the gas carbon dioxide, a raw material for sugar production, to reach the photosynthetic tissue inside the leaf. At this scale, we can also see that each tissue has a distinct cellular structure.

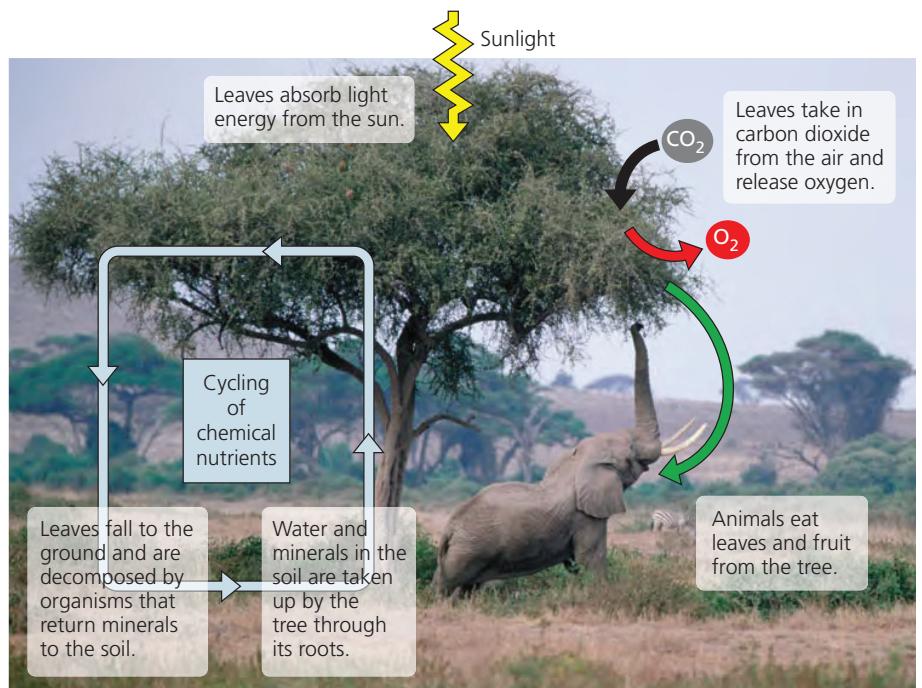
◀8 Cells

The cell is life’s fundamental unit of structure and function. Some organisms, such as amoebas and most bacteria, are single cells. Other organisms, including plants and animals, are multicellular. Instead of a single cell performing all the functions of life, a multicellular organism has a division of labor among specialized cells. A human body consists of trillions of microscopic cells of many different kinds, such as muscle cells and nerve cells, which are organized into the various specialized tissues. For example, muscle tissue consists of bundles of muscle cells. In the photo at the upper left, we see a more highly magnified view of some cells in a leaf tissue. One cell is only about 40 micrometers (μm) across. It would take about 500 of these cells to reach across a small coin. As tiny as these cells are, you can see that each contains numerous green structures called chloroplasts, which are responsible for photosynthesis.

Systems biology is relevant to the study of life at all levels. During the early years of the 20th century, biologists studying how animal bodies function (animal physiology) began integrating data on how multiple organs coordinate processes such as the regulation of sugar concentration in the blood. And in the 1960s, scientists investigating ecosystems pioneered a more mathematically sophisticated systems approach with elaborate models diagramming the network of interactions between organisms and nonliving components of ecosystems, such as salt marshes. More recently, with the sequencing of DNA from many species, systems biology has taken hold at the cellular and molecular levels, as we'll describe later when we discuss DNA.

Theme: Organisms Interact with Other Organisms and the Physical Environment

Turn back again to Figure 1.4, this time focusing on the forest. In an ecosystem, each organism interacts continuously with its environment, which includes both other organisms and physical factors. The leaves of a tree, for example, absorb light from the sun, take in carbon dioxide from the air, and release oxygen to the air (**Figure 1.5**). Both the organism and the environment are affected by the interactions between them. For example, a plant takes up water and minerals from the soil through its roots, and its roots help form soil by breaking up rocks. On a global scale, plants and other photosynthetic organisms have generated all the oxygen in the air.



▲ Figure 1.5 Interactions of an African acacia tree with other organisms and the physical environment.

A tree also interacts with other organisms, such as soil microorganisms associated with its roots, insects that live in the tree, and animals that eat its leaves and fruit. Interactions between organisms ultimately result in the cycling of nutrients in ecosystems. For example, minerals acquired by a tree will eventually be returned to the soil by other organisms that decompose leaf litter, dead roots, and other organic debris. The minerals are then available to be taken up by plants again.

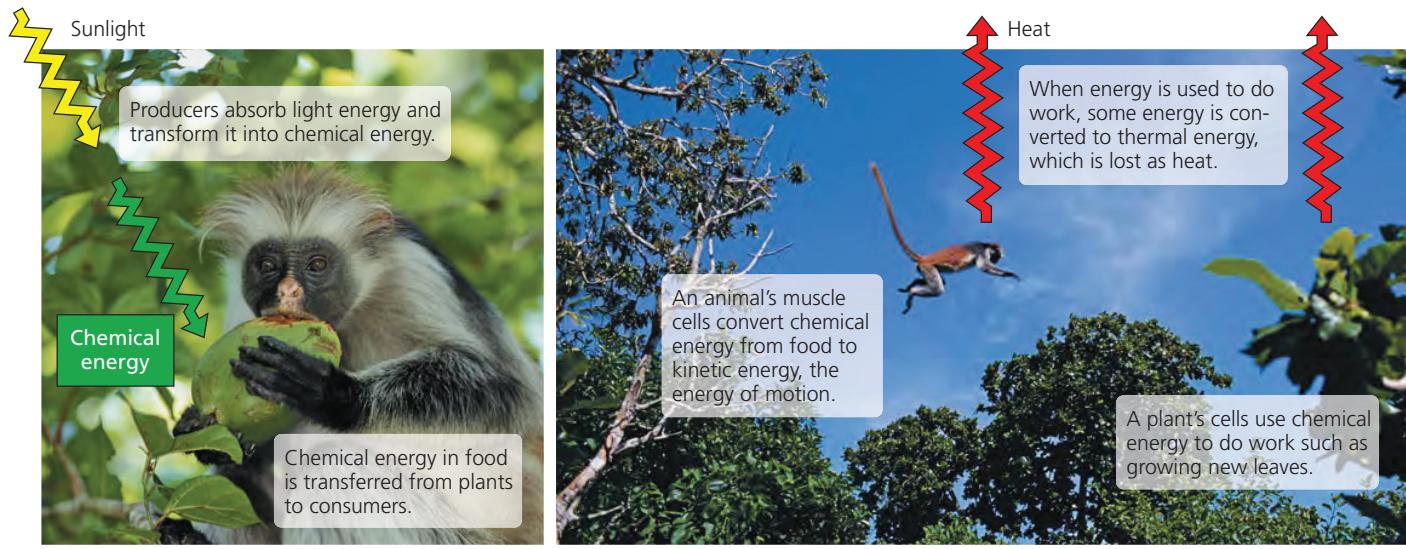
Like all organisms, we humans interact with our environment. Unfortunately, our interactions sometimes have drastic consequences. For example, since the Industrial Revolution in the 1800s, the burning of fossil fuels (coal, oil, and gas) has been increasing at an ever-accelerating pace. This practice releases gaseous compounds into the atmosphere, including prodigious amounts of carbon dioxide (CO_2). About half the human-generated CO_2 stays in the atmosphere, acting like a layer of glass around the planet that admits radiation that warms the Earth but prevents heat from radiating into outer space. Scientists estimate that the average temperature of the planet has risen 1°C since 1900 due to this “greenhouse effect,” and they project an additional rise in average global temperature of at least 3°C over the course of the 21st century.

This global warming, a major aspect of **global climate change**, has already had dire effects on life-forms and their habitats all over planet Earth. Polar bears have lost a significant portion of the ice platform from which they hunt, and there are examples of small rodents and plant species that have shifted their ranges to higher altitudes, as well as bird populations that have altered their migration schedules. Only

time will reveal the consequences of these changes. Scientists predict that even if we stopped burning fossil fuels today, it would take several centuries to return to preindustrial CO_2 levels. That scenario is highly improbable, so it is imperative that we learn all we can about the effects of global climate change on Earth and its populations. Acting as the stewards of our planet, we must strive to find ways to address this problem.

Theme: Life Requires Energy Transfer and Transformation

As you saw in Figure 1.5, a tree's leaves absorb sunlight. The input of energy from the sun makes life possible: A fundamental characteristic of living organisms is their use of energy to carry out life's activities. Moving, growing, reproducing, and the other activities of life are work, and work requires energy. In the business of living, organisms often

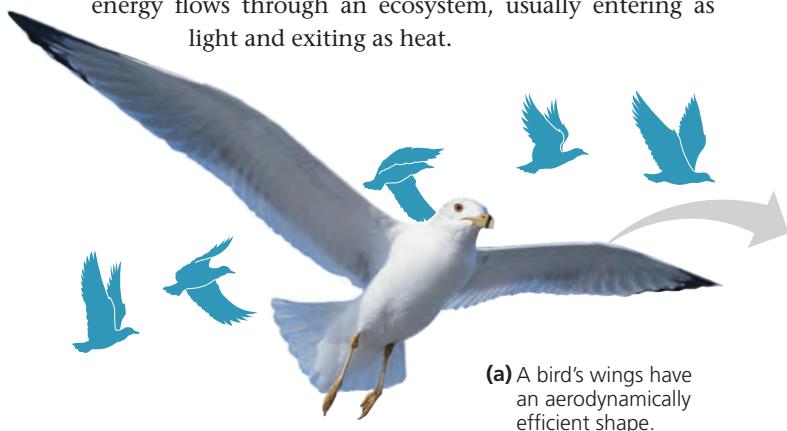


transform one form of energy to another. Chlorophyll molecules within the tree's leaves harness the energy of sunlight and use it to drive photosynthesis, converting carbon dioxide and water to sugar and oxygen. The chemical energy in sugar is then passed along by plants and other photosynthetic organisms (producers) to consumers. Consumers are organisms, such as animals, that feed on producers and other consumers (**Figure 1.6a**).

An animal's muscle cells use sugar as fuel to power movements, converting chemical energy to kinetic energy, the energy of motion (**Figure 1.6b**). The cells in a leaf use sugar to drive the process of cell proliferation during leaf growth, transforming stored chemical energy into cellular work. In both cases, some of the energy is converted to thermal energy, which dissipates to the surroundings as heat. In contrast to chemical nutrients, which recycle within an ecosystem, energy flows through an ecosystem, usually entering as light and exiting as heat.

Theme: Structure and Function Are Correlated at All Levels of Biological Organization

Another theme evident in Figure 1.4 is the idea that form fits function, which you'll recognize from everyday life. For example, a screwdriver is suited to tighten or loosen screws, a hammer to pound nails. How a device works is correlated with its structure. Applied to biology, this theme is a guide to the anatomy of life at all its structural levels. An example from Figure 1.4 is seen in the leaf: Its thin, flat shape maximizes the amount of sunlight that can be captured by its chloroplasts. Analyzing a biological structure gives us clues about what it does and how it works. Conversely, knowing the function of something provides insight into its construction. An example from the animal kingdom, the wing of a bird, provides additional instances of the structure-function theme (**Figure 1.7**). In exploring life on its different structural levels, we discover functional beauty at every turn.



▲ Figure 1.7 Form fits function in a gull's wing. (a) The shape of a bird's wings and (b) the structure of its bones make flight possible.



(b) Wing bones have a honeycombed internal structure that is strong but lightweight.

? How does form fit function in a human hand?

Theme: The Cell Is an Organism's Basic Unit of Structure and Function

In life's structural hierarchy, the cell has a special place as the lowest level of organization that can perform all activities required for life. Moreover, the activities of organisms are all based on the activities of cells. For instance, the movement of your eyes as you read this line is based on activities of muscle and nerve cells. Even a global process such as the recycling of carbon is the cumulative product of cellular activities, including the photosynthesis that occurs in the chloroplasts of leaf cells. Understanding how cells work is a major focus of biological research.

All cells share certain characteristics. For example, every cell is enclosed by a membrane that regulates the passage of materials between the cell and its surroundings. And every cell uses DNA as its genetic information. However, we can distinguish between two main forms of cells: prokaryotic cells and eukaryotic cells. The cells of two groups of microorganisms, called bacteria (singular, *bacterium*) and archaea (singular, *archaeon*), are prokaryotic. All other forms of life, including plants and animals, are composed of eukaryotic cells.

A **eukaryotic cell** is subdivided by internal membranes into various membrane-enclosed organelles (**Figure 1.8**). In most eukaryotic cells, the largest organelle is the nucleus, which contains the cell's DNA. The other organelles are located in the cytoplasm, the entire region between the nucleus and outer membrane of the cell. The chloroplast you saw in Figure 1.4 is an organelle found in eukaryotic cells that carry out photosynthesis. Prokaryotic cells are much simpler and

generally smaller than eukaryotic cells, as seen clearly in Figure 1.8. In a **prokaryotic cell**, the DNA is not separated from the rest of the cell by enclosure in a membrane-bounded nucleus. Prokaryotic cells also lack the other kinds of membrane-enclosed organelles that characterize eukaryotic cells. The properties of all organisms, whether prokaryotic or eukaryotic, are based in the structure and function of cells.

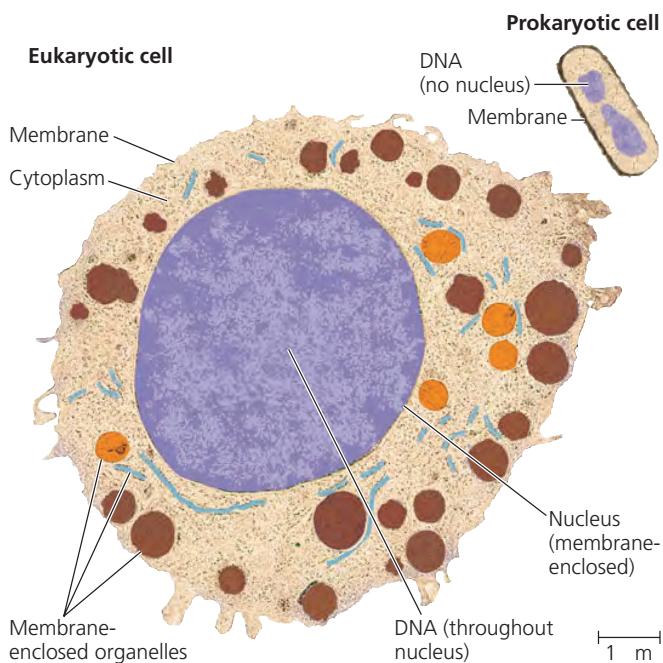
Theme: The Continuity of Life Is Based on Heritable Information in the Form of DNA

The division of cells to form new cells is the foundation for all reproduction and for the growth and repair of multicellular organisms. Inside the dividing cell in **Figure 1.9**, you can see structures called chromosomes, which are stained with a blue-glowing dye. The chromosomes have almost all of the cell's genetic material, its **DNA** (short for deoxyribonucleic acid). DNA is the substance of **genes**, the units of inheritance that transmit information from parents to offspring. Your blood group (A, B, AB, or O), for example, is the result of certain genes that you inherited from your parents.

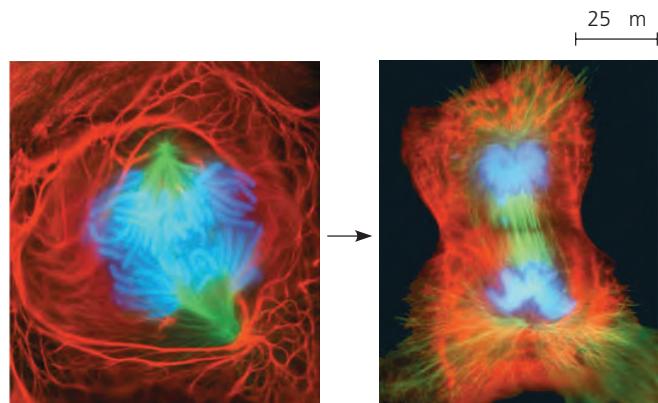
DNA Structure and Function

Each chromosome contains one very long DNA molecule, with hundreds or thousands of genes arranged along its length. The genes encode the information necessary to build other molecules in the cell, most notably proteins. Proteins play structural roles and are also responsible for carrying out cellular work. They thus establish a cell's identity.

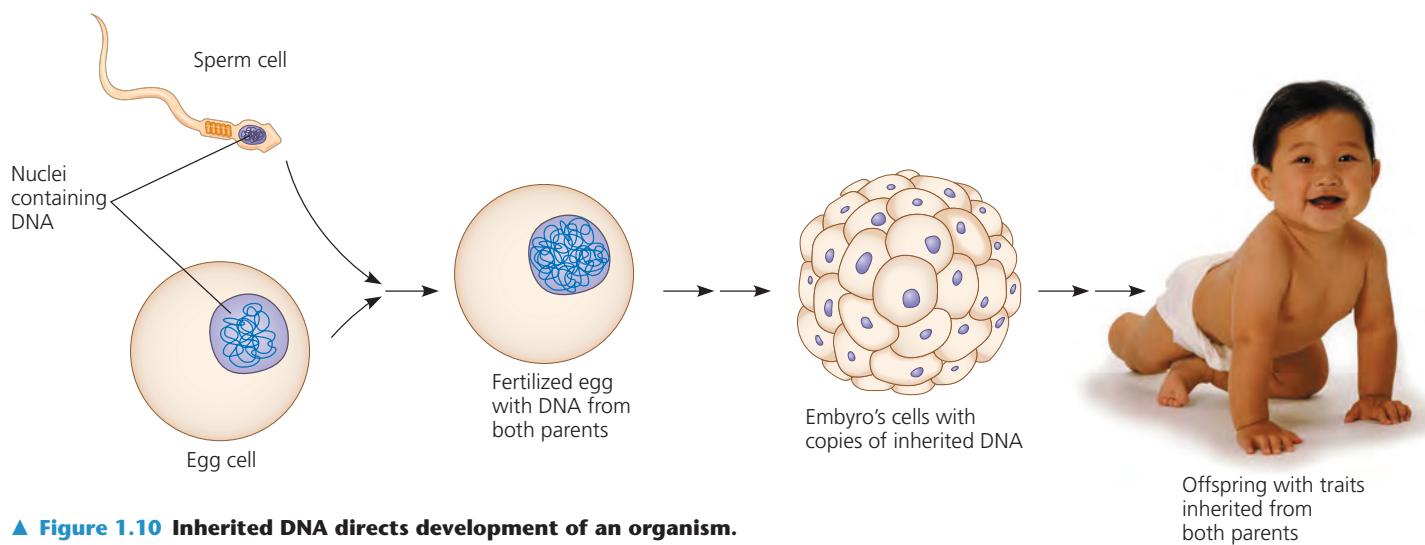
The DNA of chromosomes replicates as a cell prepares to divide, and each of the two cellular offspring inherits a complete set of genes, identical to that of the parent cell. Each of us began life as a single cell stocked with DNA inherited from our parents. Replication of that DNA with each round of cell division transmitted copies of the DNA to our trillions of cells. The DNA controls the development and maintenance of the entire organism and, indirectly, everything the organism does (**Figure 1.10**). The DNA serves as a central database.



▲ **Figure 1.8** Contrasting eukaryotic and prokaryotic cells in size and complexity.



▲ **Figure 1.9** A lung cell from a newt divides into two smaller cells that will grow and divide again.

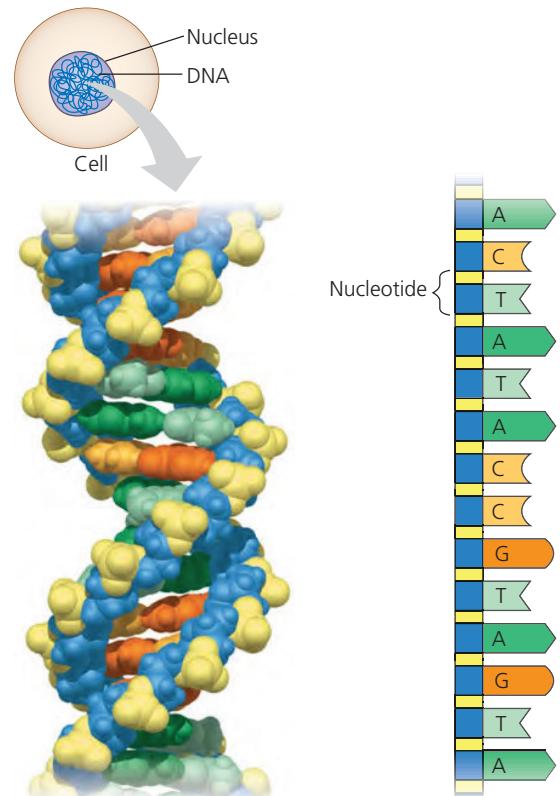


▲ **Figure 1.10 Inherited DNA directs development of an organism.**

The molecular structure of DNA accounts for its ability to store information. Each DNA molecule is made up of two long chains, called strands, arranged in a double helix. Each chain is made up of four kinds of chemical building blocks called nucleotides, abbreviated A, T, C, and G (**Figure 1.11**). The way DNA encodes information is analogous to how we arrange the letters of the alphabet into precise sequences with specific meanings. The word *rat*, for example, evokes a rodent; the words *tar* and *art*, which contain the same letters, mean very different things. We can think of nucleotides as a four-letter alphabet of inheritance. Specific sequential arrangements of these four nucleotide letters encode the information in genes, which are typically hundreds or thousands of nucleotides long.

DNA provides the blueprints for making proteins, and proteins are the main players in building and maintaining the cell and carrying out its activities. For instance, the information carried in a bacterial gene may specify a certain protein in a bacterial cell membrane, while the information in a human gene may denote a protein hormone that stimulates growth. Other human proteins include proteins in a muscle cell that drive contraction and the defensive proteins called antibodies. Enzymes, which catalyze (speed up) specific chemical reactions, are mostly proteins and are crucial to all cells.

The DNA of genes controls protein production indirectly, using a related kind of molecule called RNA as an intermediary. The sequence of nucleotides along a gene is transcribed into RNA, which is then translated into a specific protein with a unique shape and function. This entire process, by which the information in a gene directs the production of a cellular product, is called **gene expression**. In translating genes into proteins, all forms of life employ essentially the same genetic code. A particular sequence of nucleotides says the same thing in one organism as it does in another. Differences between organisms reflect differences between their nucleotide sequences rather than between their genetic codes.



(a) **DNA double helix.** This model shows each atom in a segment of DNA. Made up of two long chains of building blocks called nucleotides, a DNA molecule takes the three-dimensional form of a double helix.

(b) **Single strand of DNA.** These geometric shapes and letters are simple symbols for the nucleotides in a small section of one chain of a DNA molecule. Genetic information is encoded in specific sequences of the four types of nucleotides. (Their names are abbreviated A, T, C, and G.)

▲ **Figure 1.11 DNA: The genetic material.**

Not all RNA molecules in the cell are translated into protein; some RNAs carry out other important tasks. We have known for decades that some types of RNA are actually components of the cellular machinery that manufactures proteins. Recently, scientists have discovered whole new classes of RNA that play other roles in the cell, such as regulating the functioning of protein-coding genes. All these RNAs are specified by genes, and the process of their transcription is also referred to as gene expression. By carrying the instructions for making proteins and RNAs and by replicating with each cell division, DNA ensures faithful inheritance of genetic information from generation to generation.

Genomics: Large-Scale Analysis of DNA Sequences

The entire “library” of genetic instructions that an organism inherits is called its **genome**. A typical human cell has two similar sets of chromosomes, and each set has DNA totaling about 3 billion nucleotide pairs. If the one-letter abbreviations for the nucleotides of one strand were written in letters the size of those you are now reading, the genetic text would fill about 600 books the size of this one. Within this genomic library of nucleotide sequences are genes for about 75,000 kinds of proteins and an as yet unknown number of RNA molecules that do not code for proteins.

Since the early 1990s, the pace at which we can sequence genomes has accelerated at an almost unbelievable rate, enabled by a revolution in technology. The development of new methods and DNA-sequencing machines, such as those shown in **Figure 1.12**, have led the charge. The entire sequence of nucleotides in the human genome is now known, along with the genome sequences of many other organisms, including bacteria, archaea, fungi, plants, and other animals.

The sequencing of the human genome was heralded as a scientific and technological achievement comparable to landing the *Apollo* astronauts on the moon in 1969. But it



▲ Figure 1.12 Biology as an information science. Automatic DNA-sequencing machines and abundant computing power make the sequencing of genomes possible. This facility in Walnut Creek, California, is part of the Joint Genome Institute.

was only the beginning of an even bigger research endeavor, an effort to learn how the activities of the myriad proteins encoded by the DNA are coordinated in cells and whole organisms. To make sense of the deluge of data from genome-sequencing projects and the growing catalog of known protein functions, scientists are applying a systems approach at the cellular and molecular levels. Rather than investigating a single gene at a time, these researchers have shifted to studying whole sets of genes of a species as well as comparing genomes between species—an approach called **genomics**.

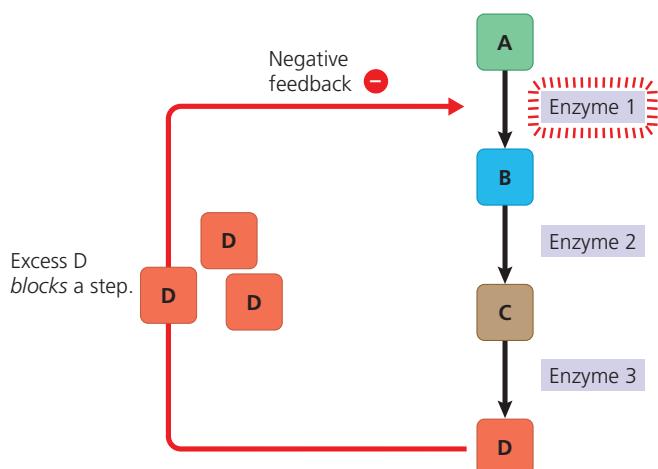
Three important research developments have made the genomic approach possible. One is “high-throughput” technology, tools that can analyze biological materials very rapidly and produce enormous amounts of data. The automatic DNA-sequencing machines that made the sequencing of the human genome possible are examples of high-throughput devices (see **Figure 1.12**). The second major development is **bioinformatics**, the use of computational tools to store, organize, and analyze the huge volume of data that result from high-throughput methods. The third key development is the formation of interdisciplinary research teams—melting pots of diverse specialists that may include computer scientists, mathematicians, engineers, chemists, physicists, and, of course, biologists from a variety of fields.

Theme: Feedback Mechanisms Regulate Biological Systems

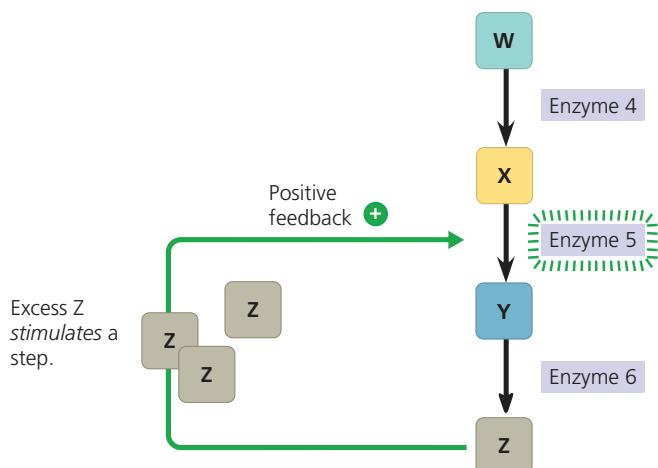
Just as a coordinated control of traffic flow is necessary for a city to function smoothly, regulation of biological processes is crucial to the operation of living systems. Consider your muscles, for instance. When your muscle cells require more energy during exercise, they increase their consumption of the sugar molecules that serve as fuel. In contrast, when you rest, a different set of chemical reactions converts surplus sugar to storage molecules.

Like most of the cell’s chemical processes, those that either decompose or store sugar are accelerated, or catalyzed, by proteins called enzymes. Each type of enzyme catalyzes a specific chemical reaction. In many cases, these reactions are linked into chemical pathways, each step with its own enzyme. How does the cell coordinate its various chemical pathways? In our example of sugar management, how does the cell match fuel supply to demand, regulating its opposing pathways of sugar consumption and storage? The key is the ability of many biological processes to self-regulate by a mechanism called feedback.

In feedback regulation, the output, or product, of a process regulates that very process. The most common form of regulation in living systems is **negative feedback**, in which accumulation of an end product of a process slows that process. For example, the cell’s breakdown of sugar generates chemical energy in the form of a substance called ATP. When a cell makes more ATP than it can use, the excess ATP “feeds back”



(a) Negative feedback. This three-step chemical pathway converts substance A to substance D. A specific enzyme catalyzes each chemical reaction. Accumulation of the final product (D) inhibits the first enzyme in the sequence, thus slowing down production of more D.



(b) Positive feedback. In a biochemical pathway regulated by positive feedback, a product stimulates an enzyme in the reaction sequence, increasing the rate of production of the product.

▲ **Figure 1.13 Regulation by feedback mechanisms.**

What would happen to the feedback system if enzyme 2 were missing?

and inhibits an enzyme near the beginning of the pathway (**Figure 1.13a**).

Though less common than processes regulated by negative feedback, there are also many biological processes regulated by **positive feedback**, in which an end product *speeds up* its own production (**Figure 1.13b**). The clotting of your blood in response to injury is an example. When a blood vessel is damaged, structures in the blood called platelets begin to aggregate at the site. Positive feedback occurs as chemicals released by the platelets attract *more* platelets. The platelet pileup then initiates a complex process that seals the wound with a clot.

Feedback is a regulatory motif common to life at all levels, from the molecular level to ecosystems and the biosphere.

Such regulation is an example of the integration that makes living systems much greater than the sum of their parts.

Evolution, the Overarching Theme of Biology

Having considered all the other themes that run through this book, let's now turn to biology's core theme—evolution. Evolution is the one idea that makes sense of everything we know about living organisms. Life has been evolving on Earth for billions of years, resulting in a vast diversity of past and present organisms. But along with the diversity we find many shared features. For example, while the sea horse, jackrabbit, hummingbird, crocodile, and giraffes in Figure 1.3 look very different, their skeletons are basically similar. The scientific explanation for this unity and diversity—and for the suitability of organisms for their environments—is evolution: the idea that the organisms living on Earth today are the modified descendants of common ancestors. In other words, we can explain traits shared by two organisms with the idea that they have descended from a common ancestor, and we can account for differences with the idea that heritable changes have occurred along the way. Many kinds of evidence support the occurrence of evolution and the theory that describes how it takes place. In the next section, we'll consider the fundamental concept of evolution in greater detail.

CONCEPT CHECK 1.1

- For each biological level in Figure 1.4, write a sentence that includes the next “lower” level. Example: “A community consists of *populations* of the various species inhabiting a specific area.”
- What theme or themes are exemplified by (a) the sharp spines of a porcupine, (b) the cloning of a plant from a single cell, and (c) a hummingbird using sugar to power its flight?
- WHAT IF?** For each theme discussed in this section, give an example not mentioned in the book.

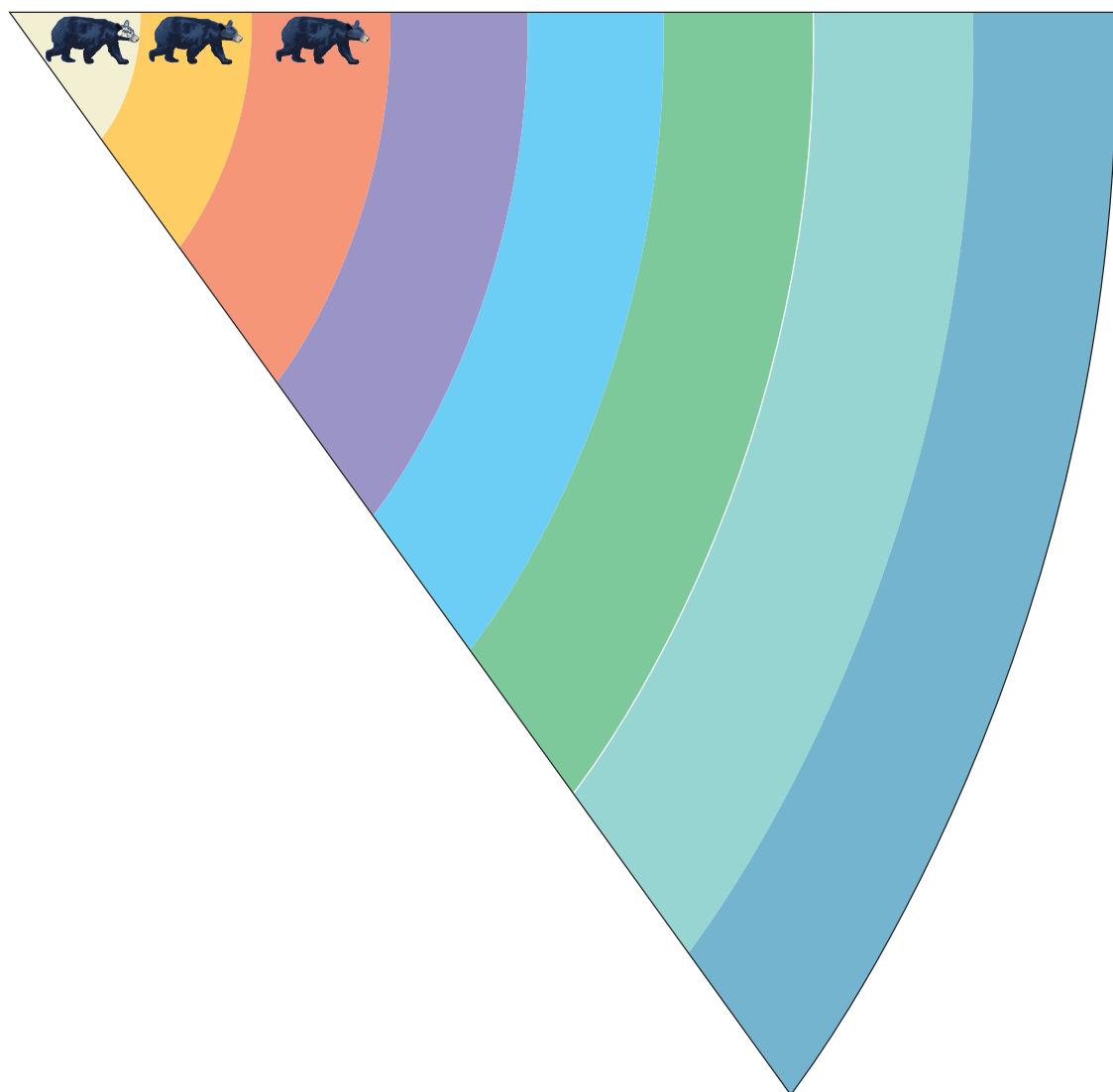
For suggested answers, see Appendix A.

CONCEPT 1.2

The Core Theme: Evolution accounts for the unity and diversity of life

EVOLUTION The list of biological themes discussed in Concept 1.1 is not absolute; some people might find a shorter or longer list more useful. There is consensus among biologists, however, as to the core theme of biology: It is evolution. To quote one of the founders of modern evolutionary theory, Theodosius Dobzhansky, “Nothing in biology makes sense except in the light of evolution.”

In addition to encompassing a hierarchy of size scales from molecules to the biosphere, biology extends across the



now, we will focus on the big picture by considering the broadest units of classification, kingdoms and domains.

The Three Domains of Life

Historically, scientists have classified the diversity of life-forms into kingdoms and finer groupings by careful comparisons of structure, function, and other obvious features. In the last few decades, new methods of assessing species relationships, such as comparisons of DNA sequences, have led to an ongoing reevaluation of the number and boundaries of kingdoms. Researchers have proposed anywhere from six kingdoms to dozens of kingdoms. While debate continues at the kingdom level, there is consensus among biologists that the kingdoms of life can be grouped into three even higher

levels of classification called domains. The three domains are named Bacteria, Archaea, and Eukarya (**Figure 1.15**).

The organisms making up two of the three domains—domain **Bacteria** and domain **Archaea**—are all prokaryotic. Most prokaryotes are single-celled and microscopic. Previously, bacteria and archaea were combined in a single kingdom because they shared the prokaryotic form of cell structure. But much evidence now supports the view that bacteria and archaea represent two very distinct branches of prokaryotic life, different in key ways that you'll learn about in Chapter 27. There is also evidence that archaea are at least as closely related to eukaryotic organisms as they are to bacteria.

All the eukaryotes (organisms with eukaryotic cells) are now grouped in domain **Eukarya**. This domain includes three kingdoms of multicellular eukaryotes: kingdoms Plantae,

▼ **Figure 1.15** The three domains of life.

(a) Domain Bacteria



Bacteria are the most diverse and widespread prokaryotes and are now classified into multiple kingdoms. Each rod-shaped structure in this photo is a bacterial cell.

(b) Domain Archaea



Many of the prokaryotes known as **archaea** live in Earth's extreme environments, such as salty lakes and boiling hot springs. Domain Archaea includes multiple kingdoms. Each round structure in this photo is an archaeal cell.

(c) Domain Eukarya



► **Kingdom Plantae** consists of terrestrial multicellular eukaryotes (land plants) that carry out photosynthesis, the conversion of light energy to the chemical energy in food.



► **Kingdom Fungi** is defined in part by the nutritional mode of its members (such as this mushroom), which absorb nutrients from outside their bodies.



► **Kingdom Animalia** consists of multicellular eukaryotes that ingest other organisms.

100 m



► **Protists** are mostly unicellular eukaryotes and some relatively simple multicellular relatives. Pictured here is an assortment of protists inhabiting pond water. Scientists are currently debating how to classify protists in a way that accurately reflects their evolutionary relationships.

Fungi, and Animalia. These three kingdoms are distinguished partly by their modes of nutrition. Plants produce their own sugars and other food molecules by photosynthesis. Fungi absorb dissolved nutrients from their surroundings; many decompose dead organisms and organic wastes (such as leaf litter and animal feces) and absorb nutrients from these sources. Animals obtain food by ingestion, which is the eating and digesting of other organisms. Animalia is, of course, the kingdom to which we belong. But neither animals, plants, nor fungi are as numerous or diverse as the single-celled eukaryotes we call protists. Although protists were once placed in a single kingdom, biologists now realize that they do not form a single natural group of species. And recent evidence shows that some protist groups are more closely related to multicellular eukaryotes such as animals and fungi than they are to each other. Thus, the recent taxonomic trend has been to split the protists into several groups.

Unity in the Diversity of Life

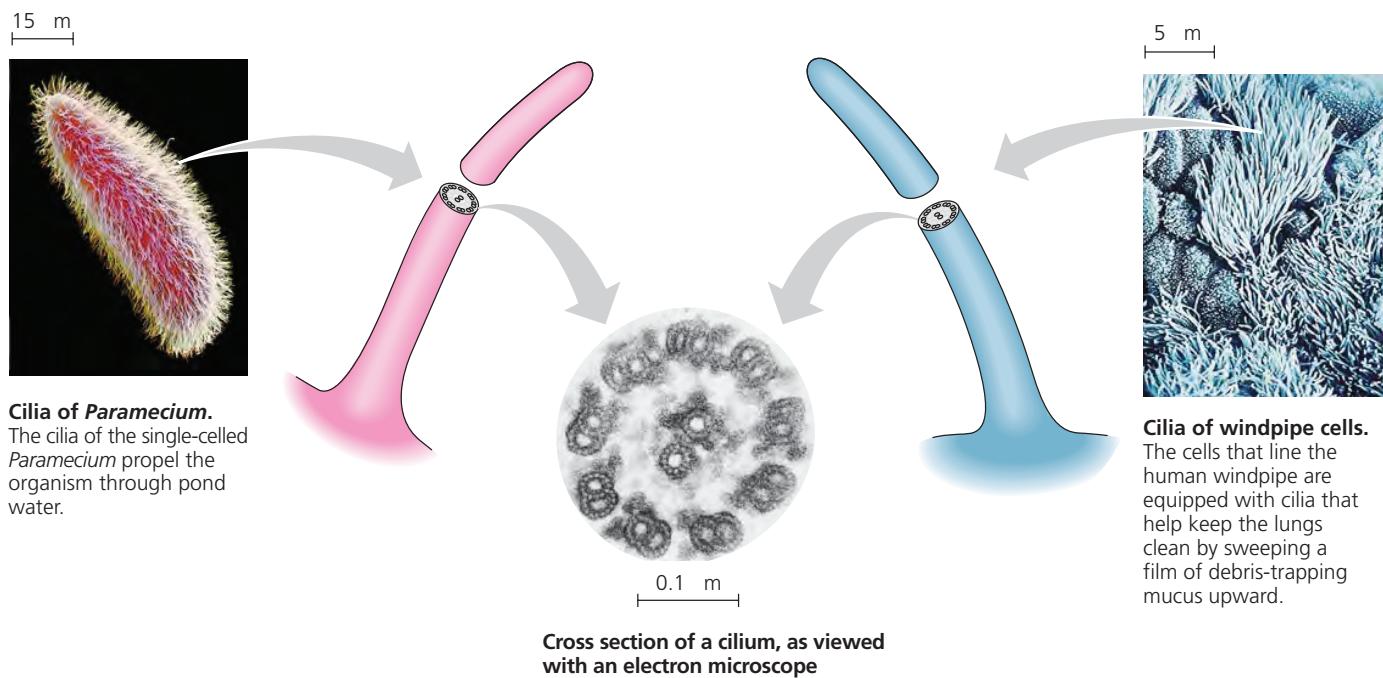
As diverse as life is, it also displays remarkable unity. Earlier we mentioned both the similar skeletons of different vertebrate animals and the universal genetic language of DNA (the genetic code). In fact, similarities between organisms are evident at all levels of the biological hierarchy. For example, unity is obvious in many features of cell structure (**Figure 1.16**).

How can we account for life's dual nature of unity and diversity? The process of evolution, explained next, illuminates both the similarities and differences in the world of life and introduces another dimension of biology: historical time.

Charles Darwin and the Theory of Natural Selection

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 (**Figure 1.17**). This evolutionary view of life came into sharp focus in November 1859, when Charles Robert Darwin published one of the most important and influential books ever written. Entitled *On the Origin of Species by Means of Natural Selection*, Darwin's book was an immediate bestseller and soon made "Darwinism," as it was dubbed at the time, almost synonymous with the concept of evolution (**Figure 1.18**).

The Origin of Species articulated two main points. The first point was that contemporary species arose from a succession of ancestors, an idea that Darwin supported with a large amount of evidence. (We will discuss the evidence for evolution in detail in Chapter 22.) Darwin called this evolutionary history of species "descent with modification." It was an insightful phrase, as it captured the duality of life's unity and diversity—unity in the kinship among species that descended



▲ Figure 1.16 An example of unity underlying the diversity of life: the architecture of cilia in eukaryotes. Cilia (singular, *cilium*) are extensions of cells that function in locomotion. They occur in eukaryotes as diverse as *Paramecium* and humans. Even organisms so different share a common architecture for their cilia, which have an elaborate system of tubules that is striking in cross-sectional views.



▲ Figure 1.17 Digging into the past. Paleontologists carefully excavate the hind leg of a long-necked dinosaur (*Rapetosaurus krausei*) from rocks in Madagascar.

from common ancestors, diversity in the modifications that evolved as species branched from their common ancestors (**Figure 1.19**). Darwin's second main point was a proposed mechanism for descent with modification. He called this evolutionary mechanism "natural selection."

Darwin synthesized his theory of natural selection from observations that by themselves were neither new nor

profound. Others had the pieces of the puzzle, but Darwin saw how they fit together. He started with the following three observations from nature: First, individuals in a population vary in their traits, many of which seem to be heritable (passed on from parents to offspring). Second, a population can produce far more offspring than can survive to produce offspring of their own. With more individuals than the environment is able to support, competition is inevitable. Third, species generally suit their environments—in other words, they are adapted to their environments. For instance, a common adaptation among birds with tough seeds as their major food source is that they have especially strong beaks.

Darwin made inferences from these observations to arrive at his theory of evolution. He reasoned that individuals with inherited traits that are best suited to the local environment are more likely to survive and reproduce than less suited individuals. Over many generations, a higher and higher proportion of individuals in a population will have the advantageous traits. Evolution occurs as the unequal reproductive success of individuals ultimately leads to adaptation to their environment, as long as the environment remains the same.

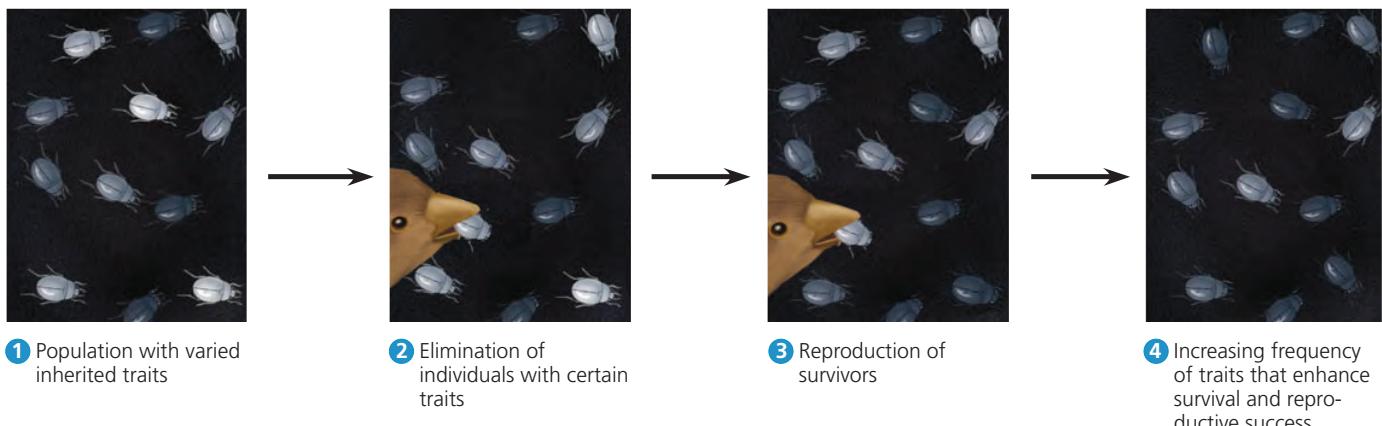
Darwin called this mechanism of evolutionary adaptation **natural selection** because the natural environment "selects" for the propagation of certain traits among naturally occurring variant traits in the population. The example



▲ Figure 1.18 Charles Darwin as a young man.



◀ Figure 1.19 Unity and diversity in the orchid family. These three orchids are variations on a common floral theme. For example, each of these flowers has a liplike petal that helps attract pollinating insects and provides a landing platform for the pollinators.



▲ **Figure 1.20 Natural selection.** This imaginary beetle population has colonized a locale where the soil has been blackened by a recent brush fire. Initially, the population varies extensively in the inherited coloration of the individuals, from very light gray to charcoal. For hungry birds that prey on the beetles, it is easiest to spot the beetles that are lightest in color.

in **Figure 1.20** illustrates the ability of natural selection to “edit” a population’s heritable variations in color. We see the products of natural selection in the exquisite adaptations of various organisms to the special circumstances of their way of life and their environment. The wings of the bat shown in **Figure 1.21** are an excellent example of adaptation.

The Tree of Life

Take another look at the skeletal architecture of the bat’s wings in **Figure 1.21**. These forelimbs, though adapted for flight, actually have all the same bones, joints, nerves, and blood vessels found in other limbs as diverse as the human arm, the horse’s foreleg, and the whale’s flipper. Indeed, all mammalian forelimbs are anatomical variations of a common architecture, much as the flowers in **Figure 1.19** are variations on an underlying “orchid” theme. Such examples of kinship connect life’s unity in diversity to the Darwinian

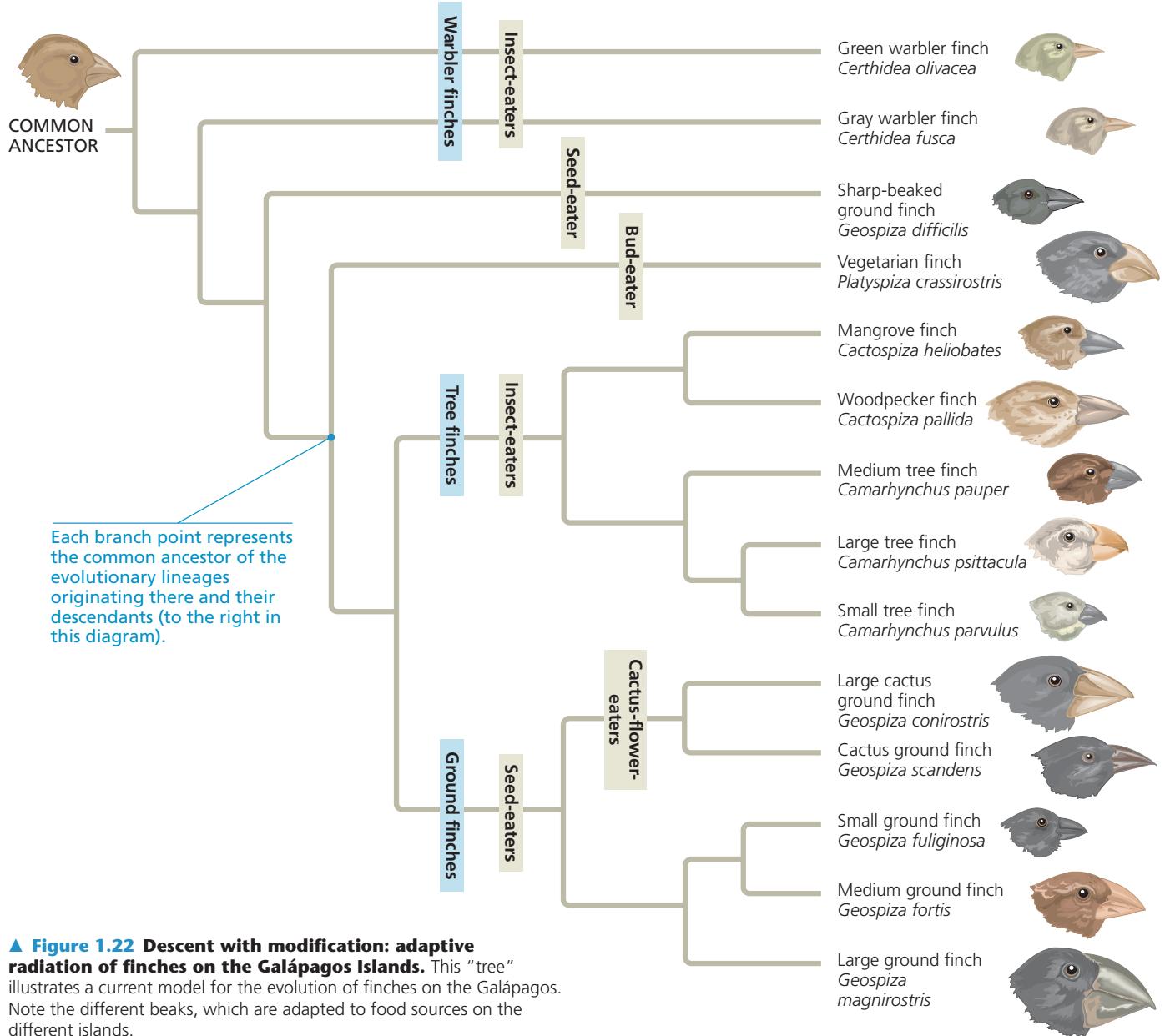
concept of descent with modification. In this view, the unity of mammalian limb anatomy reflects inheritance of that structure from a common ancestor—the “prototype” mammal from which all other mammals descended. The diversity of mammalian forelimbs results from modification by natural selection operating over millions of generations in different environmental contexts. Fossils and other evidence corroborate anatomical unity in supporting this view of mammalian descent from a common ancestor.

Darwin proposed that natural selection, by its cumulative effects over long periods of time, could cause an ancestral species to give rise to two or more descendant species. This could occur, for example, if one population fragmented into several subpopulations isolated in different environments. In these separate arenas of natural selection, one species could gradually radiate into multiple species as the geographically isolated populations adapted over many generations to different sets of environmental factors.

The “family tree” of 14 finches in **Figure 1.22** illustrates a famous example of adaptive radiation of new species from a common ancestor. Darwin collected specimens of these birds during his 1835 visit to the remote Galápagos Islands, 900 kilometers (km) off the Pacific coast of South America. These relatively young, volcanic islands are home to many species of plants and animals found nowhere else in the world, though most Galápagos organisms are clearly related to species on the South American mainland. After volcanism built the Galápagos several million years ago, finches probably diversified on the various islands from an ancestral finch species that by chance reached the archipelago from elsewhere. (Once thought to have originated on the mainland of South America like many Galápagos organisms, the ancestral finches are now thought to have come from the West Indies—islands of the Caribbean that were once much closer to the Galápagos than they are now.)



▲ **Figure 1.21 Evolutionary adaptation.** Bats, the only mammals capable of active flight, have wings with webbing between extended “fingers.” In the Darwinian view of life, such adaptations are refined over time by natural selection.



▲ Figure 1.22 Descent with modification: adaptive radiation of finches on the Galápagos Islands. This “tree” illustrates a current model for the evolution of finches on the Galápagos. Note the different beaks, which are adapted to food sources on the different islands.

Years after Darwin’s collection of Galápagos finches, researchers began to sort out the relationships among the finch species, first from anatomical and geographic data and more recently with the help of DNA sequence comparisons.

Biologists’ diagrams of evolutionary relationships generally take treelike forms, though today biologists usually turn the trees sideways as in Figure 1.22. Tree diagrams make sense: Just as an individual has a genealogy that can be diagrammed as a family tree, each species is one twig of a branching tree of life extending back in time through ancestral species more and more remote. Species that are very similar, such as the Galápagos finches, share a common ancestor

at a relatively recent branch point on the tree of life. But through an ancestor that lived much farther back in time, finches are related to sparrows, hawks, penguins, and all other birds. And birds, mammals, and all other vertebrates share a common ancestor even more ancient. We find evidence of still broader relationships in such similarities as the identical construction of all eukaryotic cilia (see Figure 1.16). Trace life back far enough, and there are only fossils of the primeval prokaryotes that inhabited Earth over 3.5 billion years ago. We can recognize their vestiges in our own cells—in the universal genetic code, for example. All of life is connected through its long evolutionary history.

CONCEPT CHECK 1.2

- How is a mailing address analogous to biology's hierarchical taxonomic system?
- Explain why "editing" is an appropriate metaphor for how natural selection acts on a population's heritable variation.
- WHAT IF?** The three domains you learned about in Concept 1.2 can be represented in the tree of life as the three main branches, with three subbranches on the eukaryotic branch being the kingdoms Plantae, Fungi, and Animalia. What if fungi and animals are more closely related to each other than either of these kingdoms is to plants—as recent evidence strongly suggests? Draw a simple branching pattern that symbolizes the proposed relationship between these three eukaryotic kingdoms.

For suggested answers, see Appendix A.

CONCEPT 1.3

In studying nature, scientists make observations and then form and test hypotheses

The word *science* is derived from a Latin verb meaning "to know." **Science** is a way of knowing—an approach to understanding the natural world. It developed out of our curiosity about ourselves, other life-forms, our planet, and the universe. Striving to understand seems to be one of our basic urges.

At the heart of science is **inquiry**, a search for information and explanation, often focusing on specific questions. Inquiry drove Darwin to seek answers in nature for how species adapt to their environments. And today inquiry drives the genomic analyses that are helping us understand biological unity and diversity at the molecular level. In fact, the inquisitive mind is the engine that drives all progress in biology.

There is no formula for successful scientific inquiry, no single scientific method with a rule book that researchers must rigidly follow. As in all quests, science includes elements of challenge, adventure, and luck, along with careful planning, reasoning, creativity, cooperation, competition, patience, and the persistence to overcome setbacks. Such diverse elements of inquiry make science far less structured than most people realize. That said, it is possible to distill certain characteristics that help to distinguish science from other ways of describing and explaining nature.

Scientists attempt to understand how natural phenomena work using a process of inquiry that includes making observations, forming logical hypotheses, and testing them. The process is necessarily repetitive: In testing a hypothesis, more observations may force formation of a new hypothesis or revision of the original one, and further testing. In this way,

scientists circle closer and closer to their best estimation of the laws governing nature.

Making Observations

In the course of their work, scientists describe natural structures and processes as accurately as possible through careful observation and analysis of data. The observations are often valuable in their own right. For example, a series of detailed observations have shaped our understanding of cell structure, and another set of observations are currently expanding our databases of genomes of diverse species.

Types of Data

Observation is the use of the senses to gather information, either directly or indirectly with the help of tools such as microscopes that extend our senses. Recorded observations are called **data**. Put another way, data are items of information on which scientific inquiry is based.

The term *data* implies numbers to many people. But some data are *qualitative*, often in the form of recorded descriptions rather than numerical measurements. For example, Jane Goodall spent decades recording her observations of chimpanzee behavior during field research in a Tanzanian jungle (**Figure 1.23**). She also documented her observations with photographs and movies. Along with these qualitative data, Goodall also enriched the field of animal behavior with volumes of *quantitative* data, which are generally recorded as



▲ **Figure 1.23** Jane Goodall collecting qualitative data on chimpanzee behavior. Goodall recorded her observations in field notebooks, often with sketches of the animals' behavior.

measurements. Skim through any of the scientific journals in your college library, and you'll see many examples of quantitative data organized into tables and graphs.

Inductive Reasoning

Collecting and analyzing observations can lead to important conclusions based on a type of logic called **inductive reasoning**. Through induction, we derive generalizations from a large number of specific observations. "The sun always rises in the east" is an example. And so is "All organisms are made of cells." The latter generalization, part of the so-called cell theory, was based on two centuries of microscopic observations by biologists of cells in diverse biological specimens. Careful observations and data analyses, along with the generalizations reached by induction, are fundamental to our understanding of nature.

Forming and Testing Hypotheses

Observations and inductive reasoning stimulate us to seek natural causes and explanations for those observations. What *caused* the diversification of finches on the Galápagos Islands? What *causes* the roots of a plant seedling to grow downward and the leaf-bearing shoot to grow upward? What *explains* the generalization that the sun always rises in the east? In science, such inquiry usually involves the proposing and testing of hypothetical explanations—that is, hypotheses.

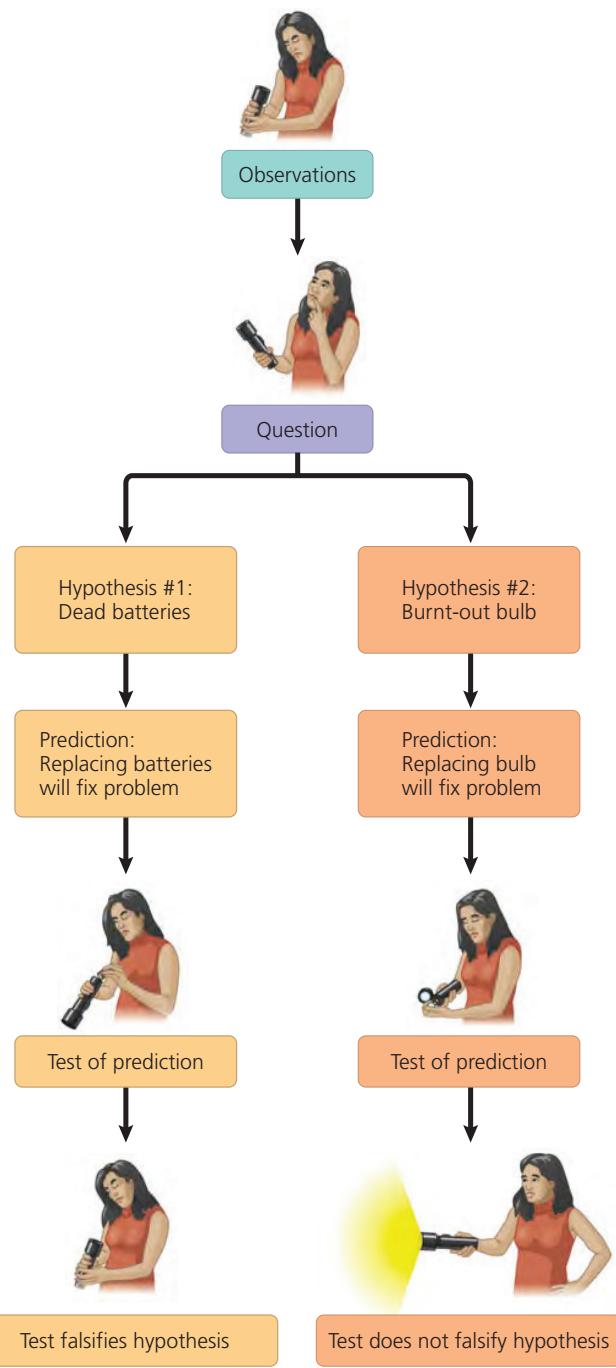
The Role of Hypotheses in Inquiry

In science, a **hypothesis** is a tentative answer to a well-framed question—an explanation on trial. It is usually a rational accounting for a set of observations, based on the available data and guided by inductive reasoning. A scientific hypothesis leads to predictions that can be tested by making additional observations or by performing experiments.

We all use hypotheses in solving everyday problems. Let's say, for example, that your flashlight fails during a camp-out. That's an observation. The question is obvious: Why doesn't the flashlight work? Two reasonable hypotheses based on your experience are that (1) the batteries in the flashlight are dead or (2) the bulb is burnt out. Each of these alternative hypotheses leads to predictions you can test with experiments. For example, the dead-battery hypothesis predicts that replacing the batteries will fix the problem. **Figure 1.24** diagrams this campground inquiry. Of course, we rarely dissect our thought processes this way when we are solving a problem using hypotheses, predictions, and experiments. But the hypothesis-based nature of science clearly has its origins in the human tendency to figure things out by trial and error.

Deductive Reasoning and Hypothesis Testing

A type of logic called deduction is built into the use of hypotheses in science. Deduction contrasts with induction,



▲ Figure 1.24 A campground example of hypothesis-based inquiry.

which, remember, is reasoning from a set of specific observations to reach a general conclusion—a process that feeds into hypothesis formation. **Deductive reasoning** is generally used after the hypothesis has been developed and involves logic that flows in the opposite direction, from the general to the specific. From general premises, we extrapolate to the specific results we should expect if the premises are true. If all organisms are made of cells (premise 1), and

humans are organisms (premise 2), then humans are composed of cells (deductive prediction about a specific case).

When using hypotheses in the scientific process, deductions usually take the form of predictions of experimental or observational results that will be found if a particular hypothesis (premise) is correct. We then test the hypothesis by carrying out the experiments or observations to see whether or not the results are as predicted. This deductive testing takes the form of “*If . . . then*” logic. In the case of the flashlight example: *If* the dead-battery hypothesis is correct and you replace the batteries with new ones, *then* the flashlight should work.

The flashlight inquiry demonstrates a key point about the use of hypotheses in science: that the initial observations may give rise to multiple hypotheses. The ideal is to design experiments to test all these candidate explanations. In addition to the two explanations tested in Figure 1.24, for instance, another of the many possible alternative hypotheses is that *both* the batteries *and* the bulb are bad. What does this hypothesis predict about the outcome of the experiments in Figure 1.24? What additional experiment would you design to test this hypothesis of multiple malfunctions?

We can mine the flashlight scenario for yet another important lesson about the scientific inquiry process. The burnt-out bulb hypothesis stands out as the most likely explanation, but notice that the testing supports that hypothesis *not* by proving that it is correct, but rather by not eliminating it through falsification (proving it false). Perhaps the first bulb was simply loose, so it wasn’t making electrical contact, and the new bulb was inserted correctly. We could attempt to falsify the burnt-out bulb hypothesis by trying another experiment—removing the original bulb and carefully reinstalling it. If the flashlight still doesn’t work, the burnt-out bulb hypothesis can stand. But no amount of experimental testing can *prove* a hypothesis beyond a shadow of doubt, because it is impossible to test *all* alternative hypotheses. A hypothesis gains credibility by surviving multiple attempts to falsify it while alternative hypotheses are eliminated (falsified) by testing.

Questions That Can and Cannot Be Addressed by Science

Scientific inquiry is a powerful way to learn about nature, but there are limitations to the kinds of questions it can answer. The flashlight example illustrates two important qualities of scientific hypotheses. First, a hypothesis must be *testable*; there must be some way to check the validity of the idea. Second, a hypothesis must be *falsifiable*; there must be some observation or experiment that could reveal if such an idea is actually *not* true. The hypothesis that dead batteries are the sole cause of the broken flashlight could be falsified by replacing the old batteries with new ones and finding that the flashlight still doesn’t work.

Not all hypotheses meet the criteria of science: You wouldn’t be able to devise a test to falsify the hypothesis that invisible campground ghosts are fooling with your flashlight! Because

science requires natural explanations for natural phenomena, it can neither support nor falsify hypotheses that angels, ghosts, or spirits, whether benevolent or evil, cause storms, rainbows, illnesses, and cures. Such supernatural explanations are simply outside the bounds of science, as are religious matters, which are issues of personal faith.

The Flexibility of the Scientific Method

The flashlight example of Figure 1.24 traces an idealized process of inquiry called *the scientific method*. We can recognize the elements of this process in most of the research articles published by scientists, but rarely in such structured form. Very few scientific inquiries adhere rigidly to the sequence of steps prescribed by the “textbook” scientific method. For example, a scientist may start to design an experiment, but then backtrack upon realizing that more preliminary observations are necessary. In other cases, puzzling observations simply don’t prompt well-defined questions until other research places those observations in a new context. For example, Darwin collected specimens of the Galápagos finches, but it wasn’t until years later, as the idea of natural selection began to gel, that biologists began asking key questions about the history of those birds.

Moreover, scientists sometimes redirect their research when they realize they have been asking the wrong question. For example, in the early 20th century, much research on schizophrenia and manic-depressive disorder (now called bipolar disorder) got sidetracked by focusing too much on the question of how life experiences might cause these serious maladies. Research on the causes and potential treatments became more productive when it was refocused on questions of how certain chemical imbalances in the brain contribute to mental illness. To be fair, we acknowledge that such twists and turns in scientific inquiry become more evident with the advantage of historical perspective.

It is important for you to get some experience with the power of the scientific method—by using it for some of the laboratory inquiries in your biology course, for example. But it is also important to avoid stereotyping science as a lock-step adherence to this method.

A Case Study in Scientific Inquiry: Investigating Mimicry in Snake Populations

Now that we have highlighted the key features of scientific inquiry—making observations and forming and testing hypotheses—you should be able to recognize these features in a case study of actual scientific research.

The story begins with a set of observations and inductive generalizations. Many poisonous animals are brightly colored, often with distinctive patterns that stand out against the background. This is called *warning coloration* because it apparently signals “dangerous species” to potential predators. But

there are also mimics. These imposters look like poisonous species but are actually harmless. A question that follows from these observations is: What is the function of such mimicry? A reasonable hypothesis is that the “deception” is an evolutionary adaptation that reduces the harmless animal’s risk of being eaten because predators mistake it for the poisonous species. This hypothesis was first formulated by British scientist Henry Bates in 1862.

As obvious as this hypothesis may seem, it has been relatively difficult to test, especially with field experiments. But in 2001, biologists David and Karin Pfennig, of the University of North Carolina, along with William Harcombe, an undergraduate, designed a simple but elegant set of field experiments to test Bates’s mimicry hypothesis.

The team investigated a case of mimicry among snakes that live in North and South Carolina (**Figure 1.25**). A venomous snake called the eastern coral snake has warning coloration: bold, alternating rings of red, yellow (or white), and black. (The word *venomous* is used when a poisonous species delivers their poison actively, by stinging, stabbing, or biting.) Predators rarely attack these coral snakes. It is unlikely that the predators learn this avoidance behavior by trial and

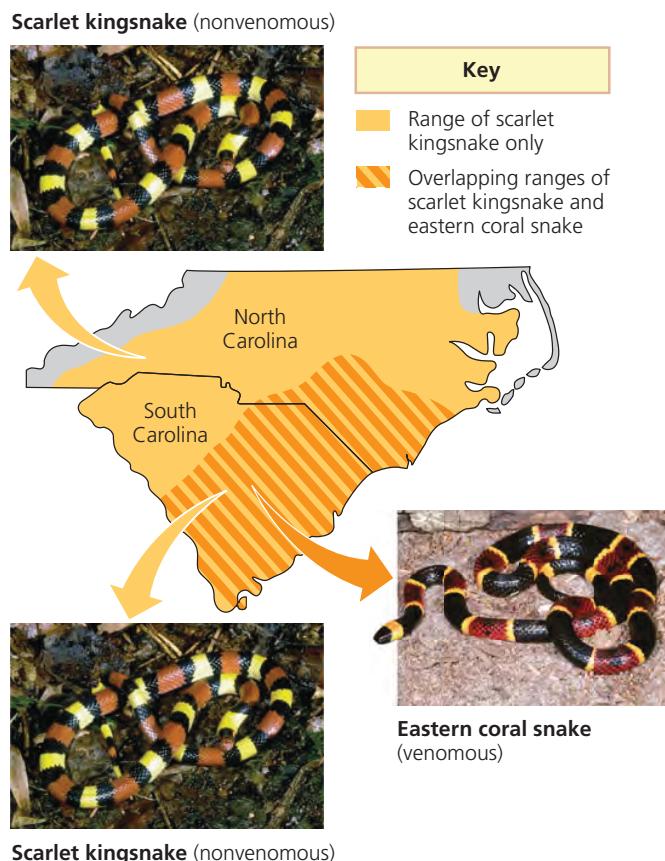
error, as a first encounter with a coral snake is usually deadly. In areas where coral snakes live, natural selection has apparently increased the frequency of predators that have inherited an instinctive avoidance of the coral snake’s coloration. A nonvenomous snake named the scarlet kingsnake mimics the ringed coloration of the coral snake.

Both types of snakes live in the Carolinas, but the kingsnakes’ geographic range also extends into regions where no coral snakes are found (see Figure 1.25). The geographic distribution of the snakes made it possible to test the key prediction of the mimicry hypothesis. Avoiding snakes with warning coloration is an adaptation we expect to be present only in predator populations that evolved in areas where the venomous coral snakes are present. Therefore, mimicry should help protect kingsnakes from predators *only in regions where coral snakes also live*. The mimicry hypothesis predicts that predators adapted to the warning coloration of coral snakes will attack kingsnakes less frequently than will predators in areas where coral snakes are absent.

Field Experiments with Artificial Snakes

To test the prediction, Harcombe made hundreds of artificial snakes out of wire covered with plasticine. He fashioned two versions of fake snakes: an *experimental group* with the red, black, and white ring pattern of kingsnakes and a *control group* of plain brown artificial snakes as a basis of comparison (**Figure 1.26**).

The researchers placed equal numbers of the two types of artificial snakes in field sites throughout North and South



▲ Figure 1.25 The geographic ranges of a venomous snake and its mimic. The scarlet kingsnake (*Lampropeltis triangulum*) mimics the warning coloration of the venomous eastern coral snake (*Micruurus fulvius*).



(a) Artificial kingsnake



(b) Brown artificial snake that has been attacked

▲ Figure 1.26 Artificial snakes used in field experiments to test the mimicry hypothesis. A bear has chewed on the brown artificial snake in (b).

Carolina, including the region where coral snakes are absent. After four weeks, the scientists retrieved the fake snakes and recorded how many had been attacked by looking for bite or claw marks. The most common predators were foxes, coyotes, and raccoons, but black bears also attacked some of the artificial snakes (see Figure 1.26b).

The data fit the key prediction of the mimicry hypothesis. Compared to the brown artificial snakes, the ringed artificial snakes were attacked by predators less frequently only in field sites within the geographic range of the venomous coral snakes. **Figure 1.27** summarizes the field experiments that the researchers carried out. This figure also introduces a format we will use throughout the book for other examples of biological inquiry.

Experimental Controls and Repeatability

The snake mimicry experiment is an example of a **controlled experiment**, one that is designed to compare an experimental group (the artificial kingsnakes, in this case) with a control group (the brown artificial snakes). Ideally, the experimental and control groups differ only in the one factor the experiment is designed to test—in our example, the effect of the snakes' coloration on the behavior of predators. Without the control group, the researchers would not have been able to rule out other factors as causes of the more frequent attacks on the artificial kingsnakes—such as different numbers of predators or different temperatures in the different test areas. The clever experimental design left coloration as the only factor that could account for the low predation rate on the artificial kingsnakes placed within the range of coral snakes. It was not the absolute number of attacks on the artificial kingsnakes that counted, but the difference between that number and the number of attacks on the brown snakes.

A common misconception is that the term *controlled experiment* means that scientists control the experimental environment to keep everything constant except the one variable being tested. But that's impossible in field research and not realistic even in highly regulated laboratory environments. Researchers usually "control" unwanted variables not by *eliminating* them through environmental regulation, but by *cancelling out* their effects by using control groups.

Another hallmark of science is that the observations and experimental results must be repeatable. Observations that can't be verified may be interesting or even entertaining, but they cannot count as evidence in scientific inquiry. The headlines of supermarket tabloids would have you believe that humans are occasionally born with the head of a dog and that some of your classmates are extraterrestrials. The unconfirmed eyewitness accounts and the computer-rigged photos are amusing but unconvincing. In science, evidence from observations and experiments is only convincing if it stands up to the criterion of repeatability. The scientists who investigated snake mimicry in the Carolinas obtained similar data when they

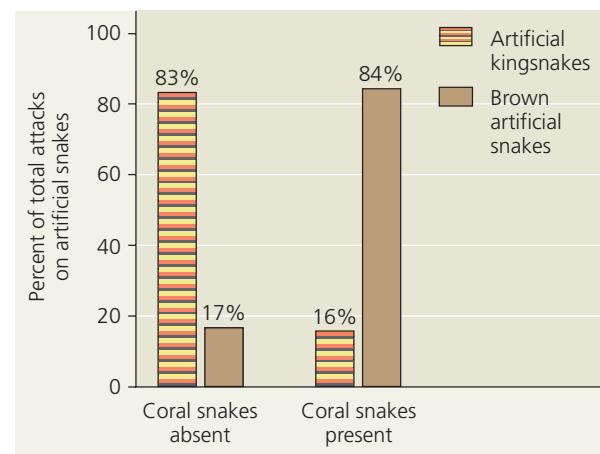
▼ **Figure 1.27**

INQUIRY

Does the presence of venomous coral snakes affect predation rates on their mimics, kingsnakes?

EXPERIMENT David Pfennig and his colleagues made artificial snakes to test a prediction of the mimicry hypothesis: that kingsnakes benefit from mimicking the warning coloration of venomous coral snakes only in regions where coral snakes are present. The researchers placed equal numbers of artificial kingsnakes (experimental group) and brown artificial snakes (control group) at 14 field sites, half in the area where the two snakes cohabit and half in the area where coral snakes are absent. The researchers recovered the artificial snakes after four weeks and tabulated predation data based on teeth and claw marks on the snakes.

RESULTS In field sites where coral snakes are absent, most attacks were on artificial kingsnakes. Where coral snakes were present, most attacks were on brown artificial snakes.



CONCLUSION The field experiments support the mimicry hypothesis by not falsifying the prediction, which was that mimicking coral snakes is effective only in areas where coral snakes are present. The experiments also tested an alternative hypothesis: that predators generally avoid all snakes with brightly colored rings. That hypothesis was falsified by the data showing that in areas without coral snakes, the ringed coloration failed to repel predators. (The fake kingsnakes may have been attacked more often in those areas because their bright pattern made them easier to spot than the brown fakes.)

SOURCE D. W. Pfennig, W. R. Harcombe, and K. S. Pfennig, Frequency-dependent Batesian mimicry, *Nature* 410:323 (2001).

INQUIRY IN ACTION Read and analyze the original paper in *Inquiry in Action: Interpreting Scientific Papers*.

See the related Experimental Inquiry Tutorial in MasteringBiology.

WHAT IF? What experimental results would you predict if predators throughout the Carolinas avoided all snakes with brightly colored ring patterns?

repeated their experiments with different species of coral snakes and kingsnakes in Arizona. And *you* should be able to obtain similar results if you were to repeat the snake experiments.

Theories in Science

"It's just a theory!" Our everyday use of the term *theory* often implies an untested speculation. But the term *theory* has a different meaning in science. What is a scientific theory, and how is it different from a hypothesis or from mere speculation?

First, a scientific **theory** is much broader in scope than a hypothesis. *This* is a hypothesis: "Mimicking the coloration of venomous snakes is an adaptation that protects nonvenomous snakes from predators." But *this* is a theory: "Evolutionary adaptations arise by natural selection." Darwin's theory of natural selection accounts for an enormous diversity of adaptations, including mimicry.

Second, a theory is general enough to spin off many new, specific hypotheses that can be tested. For example, two researchers at Princeton University, Peter and Rosemary Grant, were motivated by the theory of natural selection to test the specific hypothesis that the beaks of Galápagos finches evolve in response to changes in the types of available food. (Their results supported their hypothesis; see p. 469.)

And third, compared to any one hypothesis, a theory is generally supported by a much greater body of evidence. Those theories that become widely adopted in science (such as the theory of natural selection) explain a great diversity of observations and are supported by a vast accumulation of evidence. In fact, scrutiny of theories continues through testing of the specific, falsifiable hypotheses they spawn.

In spite of the body of evidence supporting a widely accepted theory, scientists must sometimes modify or even reject theories when new research methods produce results that don't fit. For example, the theory of biological diversity that lumped bacteria and archaea together as a kingdom of prokaryotes began to erode when new methods for comparing cells and molecules made it possible to test some of the hypothetical relationships between organisms that were based on the theory. If there is "truth" in science, it is conditional, based on the preponderance of available evidence.

CONCEPT CHECK 1.3

1. Contrast inductive reasoning with deductive reasoning.
2. In the snake mimicry experiment, what is the variable?
3. Why is natural selection called a theory?
4. **WHAT IF?** Suppose you extended the snake mimicry experiment to an area of Virginia where neither type of snake is known to live. What results would you predict at your field site?

For suggested answers, see Appendix A.

CONCEPT 1.4

Science benefits from a cooperative approach and diverse viewpoints

Movies and cartoons sometimes portray scientists as loners working in isolated labs. In reality, science is an intensely social activity. Most scientists work in teams, which often include both graduate and undergraduate students (Figure 1.28). And to succeed in science, it helps to be a good communicator. Research results have no impact until shared with a community of peers through seminars, publications, and websites.

Building on the Work of Others

The great scientist Sir Isaac Newton once said: "To explain all nature is too difficult a task for any one man or even for any one age. 'Tis much better to do a little with certainty, and leave the rest for others that come after you. . . ." Anyone who becomes a scientist, driven by curiosity about how nature works, is sure to benefit greatly from the rich storehouse of discoveries by others who have come before.

Scientists working in the same research field often check one another's claims by attempting to confirm observations or repeat experiments. If experimental results cannot be repeated by scientific colleagues, this failure may reflect some underlying weakness in the original claim, which will then have to be revised. In this sense, science polices itself. Integrity and adherence to high professional standards in reporting results are central to the scientific endeavor. After all, the validity of experimental data is key to designing further lines of inquiry.

It is not unusual for several scientists to converge on the same research question. Some scientists enjoy the challenge of being first with an important discovery or key experiment, while others derive more satisfaction from cooperating with fellow scientists working on the same problem.



▲ **Figure 1.28** **Science as a social process.** In laboratory meetings, lab members help each other interpret data, troubleshoot experiments, and plan future lines of inquiry.

Cooperation is facilitated when scientists use the same organism. Often it is a widely used **model organism**—a species that is easy to grow in the lab and lends itself particularly well to the questions being investigated. Because all organisms are evolutionarily related, lessons learned from a model organism are often widely applicable. For example, genetic studies of the fruit fly *Drosophila melanogaster* have taught us a lot about how genes work in other species, including humans. Some other popular model organisms are the mustard plant *Arabidopsis thaliana*, the soil worm *Caenorhabditis elegans*, the zebrafish *Danio rerio*, the mouse *Mus musculus*, and the bacterium *Escherichia coli*. As you read through this book, note the many contributions that these and other model organisms have made to the study of life.

Biologists may come at interesting questions from different angles. Some biologists focus on ecosystems, while others study natural phenomena at the level of organisms or cells. This book is divided into units that look at biology from different levels. Yet any given problem can be addressed from many perspectives, which in fact complement each other.

As a beginning biology student, you can benefit from making connections between the different levels of biology. You can begin to develop this skill by noticing when certain topics crop up again and again in different units. One such topic is sickle-cell disease, a well-understood genetic condition that is prevalent among native inhabitants of Africa and other warm regions and their descendants. Another topic viewed at different levels in this book is global climate change, mentioned earlier in this chapter. Sickle-cell disease and global climate change will appear in several units of the book, each time addressed at a new level. We hope these recurring topics will help you integrate the material you're learning and enhance your enjoyment of biology by helping you keep the "big picture" in mind.

Science, Technology, and Society

The biology community is part of society at large, embedded in the cultural milieu of the times. Some philosophers of science argue that scientists are so influenced by cultural and political values that science is no more objective than other ways of understanding nature. At the other extreme are people who speak of scientific theories as though they were natural laws instead of human interpretations of nature. The reality of science is probably somewhere in between—rarely perfectly objective, but continuously vetted through the expectation that observations and experiments be repeatable and hypotheses be testable and falsifiable.

The relationship of science to society becomes clearer when we add technology to the picture. Though science and technology sometimes employ similar inquiry patterns, their basic goals differ. The goal of science is to understand natural phenomena. In contrast, **technology** generally *applies* scientific knowledge for some specific purpose. Biologists and



▲ **Figure 1.29 DNA technology and crime scene**

investigation. In 2008, forensic analysis of DNA samples from a crime scene led to the release of Charles Chatman from prison after he had served nearly 27 years for a rape he didn't commit. The photo shows Judge John Creuzot hugging Mr. Chatman after his conviction was overturned. The details of forensic analysis of DNA will be described in Chapter 20.

other scientists usually speak of "discoveries," while engineers and other technologists more usually speak of "inventions." And the beneficiaries of those inventions include scientists, who put new technology to work in their research. Thus, science and technology are interdependent.

The potent combination of science and technology can have dramatic effects on society. Sometimes, the applications of basic research that turn out to be the most beneficial come out of the blue, from completely unanticipated observations in the course of scientific exploration. For example, discovery of the structure of DNA by Watson and Crick 60 years ago and subsequent achievements in DNA science led to the technologies of DNA manipulation that are transforming applied fields such as medicine, agriculture, and forensics (**Figure 1.29**). Perhaps Watson and Crick envisioned that their discovery would someday lead to important applications, but it is unlikely that they could have predicted exactly what all those applications would be.

The directions that technology takes depend less on the curiosity that drives basic science than on the current needs and wants of people and on the social environment of the times. Debates about technology center more on "should we do it" than "can we do it." With advances in technology come difficult choices. For example, under what circumstances is it acceptable to use DNA technology to find out if particular people have genes for hereditary diseases? Should such tests always be voluntary, or are there circumstances when genetic testing should be mandatory? Should insurance companies or employers have access to the information, as they do for many other types of personal health data? These questions are

becoming much more urgent as the sequencing of individual genomes becomes quicker and cheaper.

Such ethical issues have as much to do with politics, economics, and cultural values as with science and technology. All citizens—not only professional scientists—have a responsibility to be informed about how science works and about the potential benefits and risks of technology. The relationship between science, technology, and society increases the significance and value of any biology course.

The Value of Diverse Viewpoints in Science

Many of the technological innovations with the most profound impact on human society originated in settlements along trade routes, where a rich mix of different cultures ignited new ideas. For example, the printing press, which helped spread knowledge to all social classes and ultimately led to the book in your hands, was invented by the German Johannes Gutenberg around 1440. This invention relied on several innovations from China, including paper and ink. Paper traveled along trade routes from China to Baghdad, where technology was developed for its mass production. This technology then migrated to Europe, as did water-based ink from China, which was modified by Gutenberg to become oil-based ink. We have the cross-fertilization of diverse cultures to thank for the printing press, and the same can be said for other important inventions.

Along similar lines, science stands to gain much from embracing a diversity of backgrounds and viewpoints among its practitioners. But just how diverse a population are scientists in relation to gender, race, ethnicity, and other attributes?

The scientific community reflects the cultural standards and behaviors of society at large. It is therefore not surprising that until recently, women and certain minorities have faced huge obstacles in their pursuit to become professional scientists in many countries around the world. Over the past 50 years, changing attitudes about career choices have increased the proportion of women in biology and some other sciences, so that now women constitute roughly half of undergraduate biology majors and biology Ph.D. students. The pace has been slow at higher levels in the profession, however, and women and many racial and ethnic groups are still significantly underrepresented in many branches of science. This lack of diversity hampers the progress of science. The more voices that are heard at the table, the more robust, valuable, and productive the scientific interchange will be. The authors of this textbook welcome all students to the community of biologists, wishing you the joys and satisfactions of this very exciting and satisfying field of science—biology.

CONCEPT CHECK 1.4

- How does science differ from technology?
- WHAT IF?** The gene that causes sickle-cell disease is present in a higher percentage of residents of sub-Saharan Africa than it is among those of African descent living in the United States. The presence of this gene provides some protection from malaria, a serious disease that is widespread in sub-Saharan Africa. Discuss an evolutionary process that could account for the different percentages among residents of the two regions.

For suggested answers, see Appendix A.

1 CHAPTER REVIEW

SUMMARY OF KEY CONCEPTS

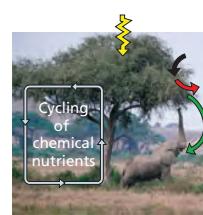
CONCEPT 1.1

The themes of this book make connections across different areas of biology (pp. 2–11)



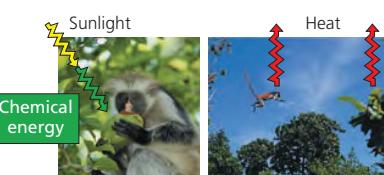
- Theme: New properties emerge at each level in the biological hierarchy**
The hierarchy of life unfolds as follows: biosphere > ecosystem > community > population > organism > organ system > organ > tissue > cell > organelle > molecule > atom. With each step upward from atoms, new properties emerge as a result

of interactions among components at the lower levels. In an approach called reductionism, complex systems are broken down to simpler components that are more manageable to study. In **systems biology**, scientists attempt to model the dynamic behavior of whole biological systems based on a study of the interactions among the system's parts.



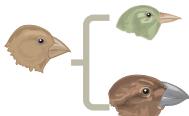
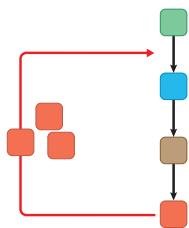
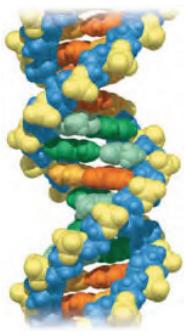
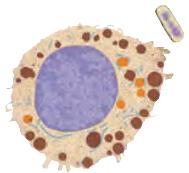
- Theme: Organisms interact with other organisms and the physical environment**

Plants take up nutrients from the soil and chemicals from the air and use energy from the sun. Interactions between plants and other organisms result in cycling of chemical nutrients within an ecosystem. One harmful outcome of human interactions with the environment has been global climate change, caused by burning of fossil fuels and increasing atmospheric CO₂.



- Theme: Life requires energy transfer and transformation**

Energy flows through an ecosystem. All organisms must perform work, which requires energy. Energy from sunlight is converted to chemical energy by producers, which is then passed on to consumers.



- Theme: Structure and function are correlated at all levels of biological organization**
The form of a biological structure suits its function and vice versa.

- Theme: The cell is an organism's basic unit of structure and function**

The cell is the lowest level of organization that can perform all activities required for life. Cells are either prokaryotic or eukaryotic. **Eukaryotic cells** contain membrane-enclosed organelles, including a DNA-containing nucleus. **Prokaryotic cells** lack such organelles.

- Theme: The continuity of life is based on heritable information in the form of DNA**

Genetic information is encoded in the nucleotide sequences of **DNA**. It is DNA that transmits heritable information from parents to offspring. DNA sequences program a cell's protein production by being transcribed into RNA and then translated into specific proteins, a process called **gene expression**. Gene expression also results in RNAs that are not translated into protein but serve other important functions. **Genomics** is the large-scale analysis of the DNA sequences within a species as well as the comparison of sequences between species.

- Theme: Feedback mechanisms regulate biological systems**

In **negative feedback**, accumulation of an end product slows the process that makes that product. In **positive feedback**, the end product stimulates the production of more product. Feedback is a type of regulation common to life at all levels, from molecules to ecosystems.

- Evolution, the Overarching Theme of Biology**

Evolution accounts for the unity and diversity of life and also for the match of organisms to their environments.

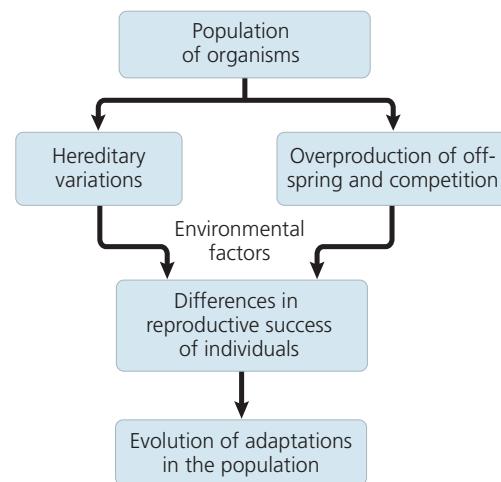
? Why is evolution considered the core theme of biology?

CONCEPT 1.2

The Core Theme: Evolution accounts for the unity and diversity of life (pp. 11–18)

- Biologists classify species according to a system of broader and broader groups. Domain **Bacteria** and domain **Archaea** consist of prokaryotes. Domain **Eukarya**, the eukaryotes, includes various groups of protists and the kingdoms Plantae, Fungi, and Animalia. As diverse as life is, there is also evidence of remarkable unity, which is revealed in the similarities between different kinds of organisms.

- Darwin proposed **natural selection** as the mechanism for evolutionary adaptation of populations to their environments.



- Each species is one twig of a branching tree of life extending back in time through ancestral species more and more remote. All of life is connected through its long evolutionary history.

? How could natural selection have led to the evolution of adaptations such as the thick, water-conserving leaves of the mother-of-pearl plant on the cover of this book?

CONCEPT 1.3

In studying nature, scientists make observations and then form and test hypotheses (pp. 18–23)

- In scientific **inquiry**, scientists make observations (collect **data**) and use **inductive reasoning** to draw a general conclusion, which can be developed into a testable **hypothesis**. **Deductive reasoning** makes predictions that can be used to test hypotheses: If a hypothesis is correct, and we test it, then we can expect the predictions to come true. Hypotheses must be testable and falsifiable; science can address neither the possibility of supernatural phenomena nor the validity of religious beliefs.
- Controlled experiments**, such as the study investigating mimicry in snake populations, are designed to demonstrate the effect of one variable by testing control groups and experimental groups that differ in only that one variable.
- A scientific **theory** is broad in scope, generates new hypotheses, and is supported by a large body of evidence.

? What are the roles of inductive and deductive reasoning in the process of scientific inquiry?

CONCEPT 1.4

Science benefits from a cooperative approach and diverse viewpoints (pp. 23–25)

- Science is a social activity. The work of each scientist builds on the work of others that have come before. Scientists must be able to repeat each other's results, so integrity is key. Biologists approach questions at different levels; their approaches complement each other.
- Technology** is a method or device that applies scientific knowledge for some specific purpose that affects society. The ultimate impact of basic research is not always immediately obvious.
- Diversity among scientists promotes progress in science.

? Explain why different approaches and diverse backgrounds among scientists are important.

TEST YOUR UNDERSTANDING

LEVEL 1: KNOWLEDGE/COMPREHENSION

1. All the organisms on your campus make up
 - a. an ecosystem.
 - b. a community.
 - c. a population.
 - d. an experimental group.
 - e. a taxonomic domain.
2. Which of the following is a correct sequence of levels in life's hierarchy, proceeding downward from an individual animal?
 - a. brain, organ system, nerve cell, nervous tissue
 - b. organ system, nervous tissue, brain
 - c. organism, organ system, tissue, cell, organ
 - d. nervous system, brain, nervous tissue, nerve cell
 - e. organ system, tissue, molecule, cell
3. Which of the following is *not* an observation or inference on which Darwin's theory of natural selection is based?
 - a. Poorly adapted individuals never produce offspring.
 - b. There is heritable variation among individuals.
 - c. Because of overproduction of offspring, there is competition for limited resources.
 - d. Individuals whose inherited characteristics best fit them to the environment will generally produce more offspring.
 - e. A population can become adapted to its environment over time.
4. Systems biology is mainly an attempt to
 - a. analyze genomes from different species.
 - b. simplify complex problems by reducing the system into smaller, less complex units.
 - c. understand the behavior of entire biological systems.
 - d. build high-throughput machines for the rapid acquisition of biological data.
 - e. speed up the technological application of scientific knowledge.
5. Protists and bacteria are grouped into different domains because
 - a. protists eat bacteria.
 - b. bacteria are not made of cells.
 - c. protists have a membrane-bounded nucleus, which bacterial cells lack.
 - d. bacteria decompose protists.
 - e. protists are photosynthetic.
6. Which of the following best demonstrates the unity among all organisms?
 - a. matching DNA nucleotide sequences
 - b. descent with modification
 - c. the structure and function of DNA
 - d. natural selection
 - e. emergent properties
7. A controlled experiment is one that
 - a. proceeds slowly enough that a scientist can make careful records of the results.
 - b. tests experimental and control groups in parallel.
 - c. is repeated many times to make sure the results are accurate.
 - d. keeps all variables constant.
 - e. is supervised by an experienced scientist.
8. Which of the following statements best distinguishes hypotheses from theories in science?
 - a. Theories are hypotheses that have been proved.
 - b. Hypotheses are guesses; theories are correct answers.
 - c. Hypotheses usually are relatively narrow in scope; theories have broad explanatory power.
 - d. Hypotheses and theories are essentially the same thing.
 - e. Theories are proved true; hypotheses are often falsified.

LEVEL 2: APPLICATION/ANALYSIS

9. Which of the following is an example of qualitative data?
 - a. The temperature decreased from 20°C to 15°C.
 - b. The plant's height is 25 centimeters (cm).
 - c. The fish swam in a zigzag motion.
 - d. The six pairs of robins hatched an average of three chicks.
 - e. The contents of the stomach are mixed every 20 seconds.
10. Which of the following best describes the logic of scientific inquiry?
 - a. If I generate a testable hypothesis, tests and observations 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.
 - e. If my experiments are set up right, they will lead to a testable hypothesis.

11. **DRAW IT** With rough sketches, draw a biological hierarchy similar to the one in Figure 1.4 but using a coral reef as the ecosystem, a fish as the organism, its stomach as the organ, and DNA as the molecule. Include all levels in the hierarchy.

LEVEL 3: SYNTHESIS/EVALUATION

12. EVOLUTION CONNECTION

A typical prokaryotic cell has about 3,000 genes in its DNA, while a human cell has about 20,500 genes. About 1,000 of these genes are present in both types of cells. Based on your understanding of evolution, explain how such different organisms could have this same subset of genes. What sorts of functions might these shared genes have?

13. SCIENTIFIC INQUIRY

Based on the results of the snake mimicry case study, suggest another hypothesis researchers might use to extend the investigation.

14. WRITE ABOUT A THEME

Evolution In a short essay (100–150 words), discuss Darwin's view of how natural selection resulted in both unity and diversity of life on Earth. Include in your discussion some of his evidence. (See p. xv for a suggested grading rubric. The rubric and tips for writing good essays can also be found in the Study Area of MasteringBiology.)

For selected answers, see Appendix A.

MasteringBIOLOGY www.masteringbiology.com

1. MasteringBiology® Assignments

Experimental Inquiry Tutorial What Can You Learn About the Process of Science from Investigating a Cricket's Chirp?

Tutorial The Scientific Method

Activities The Levels of Life Card Game • Form Fits Function: Cells • Heritable Information: DNA • Introduction to Experimental Design • GraphIt!: An Introduction to Graphing

Questions Student Misconceptions • Reading Quiz • Multiple Choice • End-of-Chapter

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Practice Tests • Cumulative Test • **BioFlix** 3-D Animations • MP3 Tutor Sessions • Videos • Activities • Investigations • Lab Media • Audio Glossary • Word Study Tools • Art

The Chemistry of Life

An Interview with Susan Solomon

Although Susan Solomon is not a biologist, her research as an atmospheric chemist has profound implications for life on Earth. Since earning degrees from the Illinois Institute of Technology and the University of California, Berkeley, Dr. Solomon has been a leader in determining the cause of the Antarctic ozone hole and in producing the 2007 report of the United Nations Intergovernmental Panel on Climate Change (IPCC), which concluded that warming of Earth's climate is unequivocal. These activities have given her a public role in communicating science to policymakers and society at large. In recognition of her scientific accomplishments, she has been awarded the U.S. National Medal of Science, the Blue Planet Prize, and, with Al Gore and the other IPCC members, the Nobel Peace Prize. A member of the U.S. National Academy of Sciences, the European Academy of Sciences, the Academy of Sciences of France, and the Royal Society of the United Kingdom, she works for the National Oceanic and Atmospheric Administration in Boulder, Colorado.



How is Earth's atmosphere important to life?

Life on Earth today could not have evolved without an atmosphere. We all know that we and many other organisms require oxygen (O_2) from the atmosphere, and plants use carbon dioxide (CO_2) to grow. The atmosphere also contains a form of oxygen called ozone that has three oxygen atoms (O_3) instead of two. Organisms would never have been able to leave the ocean and survive on land without the development of an ozone layer in the upper atmosphere. Ozone has the important property of absorbing ultraviolet (UV) light, which would otherwise cause DNA damage. Damage from UV can lead to skin cancer and cataracts; it can also harm many crops and even phytoplankton [small photosynthetic aquatic organisms].

Early in your career, you led an expedition to make measurements of the atmosphere in Antarctica. Tell us about that.

In 1985, the British Antarctic Survey reported a surprising discovery: that the springtime ozone at their station in Antarctica had fallen by 30–50% since the late 1970s, resulting in an “ozone hole”! Peo-

ple had begun to be worried about whether the ozone layer might be vulnerable to changes caused by human activity, but only very minor changes had been expected. In 1986, I had the chance to lead a new Antarctic expedition to help confirm the British data and to study the problem further. We didn't just measure ozone; we measured about a dozen other atmospheric molecules that allowed us to tell *why* the ozone was being destroyed.

What did you find out?

It turns out that the ozone chemistry in Antarctica is extremely different from what it is anywhere else. That's because Antarctica is very cold—it really is the coldest place on Earth. It's so cold that clouds form in its upper stratosphere, about 10–30 kilometers above sea level, and those clouds help convert chemicals from chlorofluorocarbons (CFCs) to ozone-damaging substances.

CFCs are synthetic compounds, made only by humans. They were used back then for a variety of purposes—for example, in refrigeration, as solvents, and as propellants for sprays. Many tons of CFCs were emitted every year. I came up with the idea that the reason an ozone hole developed in Antarctica had to do with chemical reactions that happen between a gas and a surface and that the surface in this case was the small particles that make up those stratospheric clouds. Our data supported this hypothesis. The reactions on those particles make the CFCs hundreds of times more damaging than they would be otherwise. The absence of such clouds in most other parts of the world is why we don't have ozone holes elsewhere, although stratospheric clouds form occasionally in the Arctic and there is significant ozone loss there. Scientists had been concerned since the mid-1970s that human use of CFCs might cause some ozone depletion, but they had expected a loss of only about 3–5% in 100 years.

How do CFCs destroy ozone?

When CFCs arrive at the stratosphere, which typically takes a few years, high-energy radiation up there can break them down, releasing chlorine atoms. The chlorine atoms destroy the ozone catalytically, which means that the atoms don't get used up in the process. So even if only a small amount of CFC is broken down, the tiny bit of chlorine produced can destroy an enormous amount of ozone.

In the U.N. Montreal Protocol of 1987, the nations of the world agreed to stop producing CFCs. However, the CFCs in the atmosphere disappear only very slowly; typically they hang around for 50 to 100 years. What that means is that the CFCs we've already put in the atmosphere will continue to produce an ozone hole for many decades to come, even though we're not using these substances any more. Global emissions are very near zero now, and we're beginning to see the ozone hole slowly diminish. But it will probably not go away completely until around 2060.

While the ozone hole remains, it continues to cause damage. For example, there is evidence that the phytoplankton in the Antarctic Ocean are being affected by increased UV, and the phytoplankton are the base of the main Antarctic food chain: They feed the krill, which feed the fish, which feed the penguins, seals, and whales.

Let's talk about an effect that other atmospheric changes are having—climate change.

There's no question that the planet is getting warmer. We know that, on average, our planet is about 1.4°F (0.8°C) warmer than it was 100 years ago, and this past decade has been the warmest decade in at least the last 100 years. We also know that glaciers worldwide are retreating and that sea level is rising. There's a breadth of scientific data, acquired by different techniques, that tells us that global warming really is unequivocal.

The warming has to do with the greenhouse effect, right?

We're lucky that this planet has a greenhouse effect, because if it didn't, we would be very cold indeed! Our planet is heated by the sun, and much of the infrared radiation (heat) that would otherwise

be released back into space is trapped by “greenhouse gases” in the atmosphere. This makes the planet about 30°C hotter than it would be otherwise. But of course anything can be bad if you have too much of it, and what we’re doing now is increasing the greenhouse effect of our atmosphere beyond its natural state. If we keep emitting the greenhouse gases that are causing the warming, then we will see some very significant warming in the coming century.

The main greenhouse gas we’re adding to the atmosphere is CO₂, from burning fossil fuel and to a lesser extent deforestation. We have increased the atmospheric concentration of CO₂ by about 30% compared to any value that has been found for the last 800,000 years. This has been determined by digging up ice cores in Antarctica and measuring the gases in the air bubbles trapped in the ice. So we know that we have perturbed the atmosphere in a way that the planet hasn’t seen in at least 800,000 years.

The CFCs we discussed earlier are actually the third most important greenhouse gas at present, after CO₂ and methane. Pound for pound, CFCs are much more potent as greenhouse gases than CO₂. The phase-out of CFCs since the signing of the Montreal Protocol has not only avoided a lot of ozone destruction that would otherwise have happened, but has also reduced our input of gases that cause climate change.

How is life on Earth being affected by climate change?

There are some things that we can already begin to see and talk about, but there’s an enormous amount that we still don’t know. We do know that the oceans are getting more acidic because CO₂ is taken up by the ocean and converted to carbonic acid, which can affect the ability of shellfish to make their shells. Other ocean life is also likely to be harmed by the increased acidity, such as the organisms of coral reefs. But there’s also emerging evidence that some other marine organisms may do better—lobsters, perhaps.

As a westerner I’m extremely concerned about the greatly increased population of pine beetles in the western United States. These beetles are killing pine trees in unprecedented numbers. There’s good evidence that a contributing factor to this explosion of pine beetles is global warming. I think we’re going to see more of this kind of thing. Also, it is clear that bird migration is already being affected by global warming. Whether global warming will lead to extinction of some animals is an important question. The signature extinction issue is the polar bear; as the sea ice of the Arctic decreases, the polar bear could become extinct. We don’t really know yet how much biological adaptation is possible in the time available. We’ll probably find out that there are some winner species out there and some loser species. In agriculture, many crops are sensitive to increasing temperatures. One of the relevant findings about corn is that for every degree of warming, about 10% of crop production is lost—a big change.

Does less precipitation always go along with higher temperatures?

In some places there will probably be less precipitation and in other places more. There’s a band of subtropical and tropical regions where we are pretty confident that it will get drier—for example, Mexico, the Mediterranean region, parts of Australia. In the higher latitudes, places like Canada and Norway will likely get wetter. In between, it’s harder to predict.

Tell us about the IPCC and your work on it.

The IPCC is fundamentally a mechanism for the communication of information about climate change from the science community to the policy community. It was set up in 1988 when people were beginning to recognize that climate change was a real possibility. Policymakers decided that they needed to get reliable scientific information so they could begin to talk about what to do, if anything. Every six or seven years, scientists are asked by their governments to get together and assess what we know and don’t know on the basis of the published scientific literature.

I have been involved in the IPCC since 1992, and in 2001 I was elected by the panel, representing over 100 governments, to co-chair the scientific assessment team. In a process lasting several years, we generated a detailed report summarizing the state of climate science. Our report was then reviewed by dozens of governments and more than 600 scientists. The report itself and every one of their 30,000 comments are available on the Internet. We refined and refined the draft in consideration of those comments and finalized the document in 2007.

What were the main conclusions of your 2007 report?

The first conclusion, based on many independent lines of evidence, was that the Earth is warming. There’s no doubt we are now living on a planet that is warmer than a century ago. The second main conclusion was that most—more than half—of the warming is very likely due to increases in greenhouse gases, primarily CO₂. We did a careful analysis of the uncertainties: When we say “very likely,” we mean that there’s a 90% chance or greater that most of the warming is due to emissions of greenhouse gases by human activity.

What have you learned about working at the interface of science and policy?

It’s one of the most difficult things a scientist can do. Science normally takes us into a laboratory or out into the field or into scholarly discussions with colleagues. Getting involved with policy is quite different: It takes us out of the lab and makes us much more aware of the strong emotions around many issues. In that sense, it’s a bit daunting. But it’s uplifting to see how valuable science can be in helping society make more informed choices. Scientists can help make sure that whatever it is we choose to do as a society we’re doing knowingly, not in ignorance. I appreciate all the reasons why people ask tough questions about the science.

How much do we know? What really are the uncertainties? Yes, there’s a lot at stake here, all the more reason why there has to be really good science going into it.

“There’s a breadth of scientific data, acquired by different techniques, that tells us that global warming really is unequivocal.”

Susan Solomon
(right) with
Jane Reece

