Evolution, the Themes of Biology, and Scientific Inquiry

Inquiring About Life

The dandelions shown in Figure 1.1 send their seeds aloft for dispersal. A seed is an embryo surrounded by a store of food and a protective coat. The dandelion’s seeds, shown at the lower left, are borne on the wind by parachute-like structures made from modified flower parts. The parachutes harness the wind, which carries such seeds to new locations where conditions may favor sprouting and growth. Dandelions are very successful plants, found in temperate regions worldwide.

An organism’s adaptations to its environment, such as the dandelion seed’s parachute, are the result of evolution. Evolution is the process of change that has transformed life on Earth from its earliest beginnings to the diversity of organisms living today. Because evolution is the fundamental organizing principle of biology, it is the core theme of this book.

Although biologists know a great deal about life on Earth, many mysteries remain. For instance, what processes led to the origin of flowering among plants such as the ones pictured above? Posing questions about the living world and seeking answers through 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. 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.

At the most fundamental level, we may ask: What is life? Even a child realizes that a dog or a plant is alive, while a rock or a car is not. Yet the phenomenon we call life defies a simple, one-sentence definition. We recognize life by what living things do. Figure 1.2 highlights some of the properties and processes we associate with life.

While limited to a handful of images, Figure 1.2 reminds us that the living world is wondrously varied. How do biologists 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, which accounts for life’s unity and diversity. Next, we look at scientific inquiry—how scientists ask and attempt to answer questions about the natural world. Finally, we address the culture of science and its effects on society.
The study of life reveals common themes

Biology is a subject of enormous scope, and exciting new biological discoveries are being made every day. How can you organize into a comprehensible framework all the information you'll encounter as you study the broad range of topics included in biology? Focusing on a few big ideas will help. Here, we'll list five unifying themes—ways of thinking about life that will still hold true decades from now. These unifying themes are described in greater detail in the next few pages. We hope they will serve as touchstones as you proceed through this text:

- Organization
- Information
- Energy and Matter
- Interactions
- Evolution

▶ Figure 1.3
Exploring Levels of Biological Organization

1 The Biosphere

Even from space, we can see signs of Earth's life—in the green mosaic of the forests, for example. We can also see the scale of the entire 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.

2 Ecosystems

Our first scale change brings us to a North American forest with many deciduous trees (trees that lose their leaves and grow new ones each year). A deciduous forest is an example of an ecosystem, as are grasslands, deserts, and coral reefs. 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.

3 Communities

The 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, various animals, 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 forest includes a population of sugar maple trees and a population of white-tailed deer. A community is therefore 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 deer, frog, beetle, and other forest animals. The soil teems with microorganisms such as bacteria.
Theme: New Properties Emerge at Successive Levels of Biological Organization

In Figure 1.3, we zoom in from space to take a closer and closer look at life in a deciduous forest in Ontario, Canada. This journey shows the different levels of organization recognized by biologists: The study of life extends from the global scale of the entire living planet to the microscopic scale of cells and molecules. The numbers in the figure guide you through the hierarchy of biological organization.

6 Organs and Organ Systems

The structural hierarchy of life continues to unfold as we explore the architecture of 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. The organs of complex animals and plants are organized into organ systems, each a team of organs that cooperate in a larger function. Organs consist of multiple tissues.

7 Tissues

Viewing the tissues of a leaf requires a microscope. Each tissue is 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 side of photo) is the main location of photosynthesis, the process that converts light energy to the chemical energy of sugar. The jigsaw puzzle–like “skin” on the surface of the leaf is a tissue called epidermis (right side of photo). The pores through the epidermis allow entry of the gas CO$_2$, a raw material for sugar production.

8 Cells

The cell is life’s fundamental unit of structure and function. Some organisms are single cells, while others are multicellular. A single cell performs all the functions of life, while a multicellular organism has a division of labor among specialized cells. Here we see a magnified view of cells in a leaf tissue. One cell is about 40 micrometers (μm) across—about 500 of them would 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.

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 units called atoms, represented as balls in this computer graphic of a chlorophyll molecule. Chlorophyll is the pigment molecule that makes a maple leaf green, and it absorbs sunlight during photosynthesis. Within each chloroplast, millions of chlorophyll molecules are organized into systems that convert light energy to the chemical energy of food.
Emergent Properties

Let’s reexamine Figure 1.3, beginning this time at the molecular level and then zooming out. This approach allows us to see novel properties emerge at each level that are absent from 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. The coordinated processes of photosynthesis require a specific organization of these molecules in the chloroplast. Isolated components of living systems, serving as the objects of study in a reductionist approach to biology, lack a number of significant properties that emerge at higher levels of organization.

Emergent properties are not unique to life. A box of bicycle parts won’t transport you anywhere, but if they are arranged in a certain way, you can pedal to your chosen destination. Compared with such nonliving examples, however, biological systems are far more complex, making the emergent properties of life especially challenging to study.

To explore emergent properties more fully, biologists today complement reductionism with systems biology, the exploration of a biological system by analyzing the interactions among its parts. In this context, a single leaf cell can be considered a system, as can a frog, an ant colony, or a desert ecosystem. By examining and modeling the dynamic behavior of an integrated network of components, systems biology enables us to pose new kinds of questions. For example, we can ask how a drug that lowers blood pressure affects the functioning of organs throughout the human body. At a larger scale, how does a gradual increase in atmospheric carbon dioxide alter ecosystems and the entire biosphere? Systems biology can be used to study life at all levels.

Structure and Function

At each level of the biological hierarchy, we find a correlation of structure and function. Consider the leaf shown in Figure 1.3: Its thin, flat shape maximizes the capture of sunlight by chloroplasts. More generally, 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 structure and organization. Many examples from the animal kingdom show a correlation between structure and function. For example, the hummingbird’s anatomy allows the wings to rotate at the shoulder, so hummingbirds have the ability, unique among birds, to fly backward or hover in place. While hovering, the birds can extend their long, slender beaks into flowers and feed on nectar. The elegant match of form and function in the structures of life is explained by natural selection, which we’ll explore shortly.

The Cell: An Organism’s Basic Unit of Structure and Function

In life’s structural hierarchy, the cell is the smallest unit of organization that can perform all activities required for life. In fact, the actions of organisms are all based on the functioning of cells. For instance, the movement of your eyes as you read this sentence results from the activities of muscle and nerve cells. Even a process that occurs on a global scale, such as the recycling of carbon atoms, is the product of cellular functions, including the photosynthetic activity of chloroplasts in leaf cells.

All cells share certain characteristics. For instance, every cell is enclosed by a membrane that regulates the passage of materials between the cell and its surroundings. Nevertheless, we recognize two main forms of cells: prokaryotic and eukaryotic. The cells of two groups of single-celled microorganisms—bacteria (singular, *bacterium*) and archaea (singular, *archaean*)—are prokaryotic. All other forms of life, including plants and animals, are composed of eukaryotic cells.

A eukaryotic cell contains membrane-enclosed organelles (Figure 1.4). Some organelles, such as the DNA-containing nucleus, are found in the cells of all eukaryotes; other organelles are specific to particular cell types. For example, the chloroplast in Figure 1.3 is an organelle found...
only in eukaryotic cells that carry out photosynthesis. In contrast to eukaryotic cells, a prokaryotic cell lacks a nucleus or other membrane-enclosed organelles. Another distinction is that prokaryotic cells are generally smaller than eukaryotic cells, as shown in Figure 1.4.

**Theme: Life’s Processes Involve the Expression and Transmission of Genetic Information**

Within cells, structures called chromosomes contain genetic material in the form of DNA (deoxyribonucleic acid). In cells that are preparing to divide, the chromosomes may be made visible using a dye that appears blue when bound to the DNA (Figure 1.5).

**DNA, the Genetic Material**

Each time a cell divides, the DNA is first replicated, or copied, and each of the two cellular offspring inherits a complete set of chromosomes, identical to that of the parent cell. Each chromosome contains one very long DNA molecule with hundreds or thousands of genes, each a section of the DNA of the chromosome. Transmitted from parents to offspring, genes are the units of inheritance. They encode the information necessary to build all of the molecules synthesized within a cell, which in turn establish that cell’s identity and function. Each of us began as a single cell stocked with DNA inherited from our parents. The replication of that DNA during each round of cell division transmitted copies of the DNA to what eventually became the trillions of cells of our body. As the cells grew and divided, the genetic information encoded by the DNA directed our development (Figure 1.6).

The molecular structure of DNA accounts for its ability to store information. A 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 1.7).
The way DNA encodes information is analogous to how we arrange the letters of the alphabet into words and phrases 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. Specific sequences of these four nucleotides encode the information in genes.

Many genes provide the blueprints for making proteins, which are the major players in building and maintaining the cell and carrying out its activities. For instance, a given bacterial gene may specify a particular protein (an enzyme) required to break down a certain sugar molecule, while a human gene may denote a different protein (an antibody) that helps fight off infection.

Genes control protein production indirectly, using a related molecule called RNA as an intermediary (Figure 1.8). The sequence of nucleotides along a gene is transcribed into RNA, which is then translated into a linked series of protein building blocks called amino acids. These two stages result in a specific protein with a unique shape and function. The entire process, by which the information in a gene directs the manufacture 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. Comparing the sequences in several species for a gene that codes for a particular protein can provide valuable information both about the protein and about the relationship of the species to each other, as you will see.

In addition to RNA molecules (called mRNAs) that are translated into proteins, some RNAs in the cell carry out other important tasks. For example, 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 of these RNAs are specified by genes, and the production of these RNAs 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 approximately 3 billion nucleotide pairs of DNA. If the one-letter abbreviations for the nucleotides of a set were written in letters the size of those you are now reading, the genetic text would fill about 700 biology textbooks.
Since the early 1990s, the pace at which researchers can determine the sequence of a genome has accelerated at an astounding rate, enabled by a revolution in technology. The entire sequence of nucleotides in the human genome is now known, along with the genome sequences of many other organisms, including other animals and numerous plants, fungi, bacteria, and archaea. To make sense of the deluge of data from genome-sequencing projects and the growing catalog of known gene functions, scientists are applying a systems biology approach at the cellular and molecular levels. Rather than investigating a single gene at a time, researchers study whole sets of genes (or other DNA) in one or more species—an approach called genomics. Likewise, the term proteomics refers to the study of sets of proteins and their properties. (The entire set of proteins expressed by a given cell or group of cells is called a proteome).

Three important research developments have made the genomic and proteomic approaches possible. One is “high-throughput” technology, tools that can analyze many biological samples very rapidly. The second major development is bioinformatics, the use of computational tools to store, organize, and analyze the huge volume of data that results from high-throughput methods. The third development is the formation of interdisciplinary research teams—groups of diverse specialists that may include computer scientists, mathematicians, engineers, chemists, physicists, and, of course, biologists from a variety of fields. Researchers in such teams aim to learn how the activities of all the proteins and non-translated RNAs encoded by the DNA are coordinated in cells and in whole organisms.

**Theme: Life Requires the Transfer and Transformation of Energy and Matter**

**ENERGY AND MATTER** A fundamental characteristic of living organisms is their use of energy to carry out life’s activities. Moving, growing, reproducing, and the various cellular activities of life are work, and work requires energy. The input of energy, primarily from the sun, and the transformation of energy from one form to another make life possible. A plant’s leaves absorb sunlight, and molecules within the leaves convert the energy of sunlight to the chemical energy of food, such as sugars, produced during photosynthesis. The chemical energy in the food molecules 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.

When an organism uses chemical energy to perform work, such as muscle contraction or cell division, some of that energy is lost to the surroundings as heat. As a result, energy flows one way through an ecosystem, usually entering as light and exiting as heat. In contrast, chemicals are recycled within an ecosystem (Figure 1.9). Chemicals that a plant absorbs from the air or soil may be incorporated into the plant’s body and then passed to an animal that eats the plant. Eventually, these chemicals will be returned to the environment by decomposers, such as bacteria and fungi, that break down waste products, leaf litter, and the bodies of dead organisms. The chemicals are then available to be taken up by plants again, thereby completing the cycle.

![Figure 1.9 Energy flow and chemical cycling](image)
Theme: From Ecosystems to Molecules, Interactions Are Important in Biological Systems

At any level of the biological hierarchy, interactions between the components of the system ensure smooth integration of all the parts, such that they function as a whole. This holds true equally well for the components of an ecosystem and the molecules in a cell; we’ll discuss both as examples.

Ecosystems: An Organism’s Interactions with Other Organisms and the Physical Environment

At the ecosystem level, each organism interacts with other organisms. For instance, an acacia tree interacts with soil microorganisms associated with its roots, insects that live on it, and animals that eat its leaves and fruit (Figure 1.10). In some cases, interactions between organisms are mutually beneficial. An example is the association between a sea turtle and the so-called “cleaner fish” that hover around it. The fish feed on parasites that would otherwise harm the turtle, while gaining a meal and protection from predators. Sometimes, one species benefits and the other is harmed, as when a lion kills and eats a zebra. In yet other cases, both species are harmed—for example, when two plants compete for a soil resource that is in short supply. Interactions among organisms help regulate the functioning of the ecosystem as a whole.

Organisms also interact continuously with physical factors in their environment. 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 (see Figure 1.10). The environment is also affected by the organisms living there. For instance, in addition to taking up water and minerals from the soil, the roots of a plant break up rocks as they grow, thereby contributing to the formation of soil. On a global scale, plants and other photosynthetic organisms have generated all the oxygen in the atmosphere.

Molecules: Interactions Within Organisms

At lower levels of organization, the interactions between components that make up living organisms—organs, tissues, cells, and molecules—are crucial to their smooth operation. Consider the sugar in your blood, for instance. After a meal, the level of the sugar glucose in your blood rises (Figure 1.11). The increase in blood glucose stimulates the pancreas to release insulin into the blood. Once it reaches liver or muscle cells, insulin causes excess glucose to be stored in the form of a very large carbohydrate called glycogen, reducing blood glucose level to a range that is optimal for bodily functioning. The lower blood glucose level that results no longer stimulates insulin secretion by pancreas cells. Some sugar is also used by cells for energy: When you exercise, your muscle cells increase their consumption of sugar molecules.

Interactions among the body’s molecules are responsible for most of the steps in this process. For instance, like most chemical activities in the cell, those that either decompose or store sugar are accelerated at the molecular level (catalyzed) by proteins called enzymes. Each type of enzyme...
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 through ecosystems and the biosphere. Interactions between organisms can affect system-wide processes like the growth of a population. And as we’ll see, interactions between individuals not only affect the participants, but also affect how populations evolve over time.

Evolution, the Core Theme of Biology

Having considered four of the unifying themes that run through this text (organization, information, energy and matter, and interactions), let’s now turn to biology’s core theme—evolution. Evolution is the one idea that makes logical sense of everything we know about living organisms. As we will see in Units 4 and 5 of this text, the fossil record documents the fact that 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 are many shared features. For example, while sea horses, jackrabbits, hummingbirds, and giraffes all look very different, their skeletons are organized in the same basic way. The scientific explanation for this unity and diversity—as well as for the adaptation of organisms to their environments—is evolution: the concept that the organisms living on Earth today are the modified descendants of common ancestors. In other words, we can explain the sharing of traits by two organisms with the premise that the organisms 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.

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, a loop in which the response reduces the initial stimulus. As seen in the example of insulin signaling (see Figure 1.11), the uptake of glucose by cells (the response) decreases blood glucose levels, eliminating the stimulus for insulin secretion and thereby shutting off the pathway. Thus, the output of the process negatively regulates that process.

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. 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.

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CONCEPT CHECK 1.1

1. Starting with the molecular level in Figure 1.3, write a sentence that includes components from the previous (lower) level of biological organization, for example: “A molecule consists of atoms bonded together.” Continue with organelles, moving up the biological hierarchy.

2. Identify the theme or themes exemplified by (a) the sharp quills of a porcupine, (b) the development of a multicellular organism from a single fertilized egg, and (c) a hummingbird using sugar to power its flight.

3. What if? For each theme discussed in this section, give an example not mentioned in the text.

For suggested answers, see Appendix A.
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To make sense of the diversity of life, biologists classify species into groups that are then combined into even broader groups. In the traditional “Linnaean” system, species that are very closely related, such as polar bears and brown bears, are placed in the same genus; genera (plural of genus) are grouped into families; and so on. This example classifies the species *Ursus americanus*, the American black bear. (Alternative classification schemes will be discussed in detail in Chapter 26.)

**CONCEPT 1.2**

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

**EVOlution** There is consensus among biologists that evolution is the core theme of biology. The evolutionary changes seen in the fossil record are observable facts. Furthermore, as we’ll describe, evolutionary mechanisms account for the unity and diversity of all species on Earth. 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 explores the great diversity of species that have ever lived on Earth. To understand Dobzhansky’s statement, we need to discuss how biologists think about this vast diversity.

**Classifying the Diversity of Life**

Diversity is a hallmark of life. Biologists have so far identified and named about 1.8 million species. To date, this diversity of life is known to include at least 100,000 species of fungi, 290,000 plant species, 57,000 vertebrate species (animals with backbones), and 1 million insect species (more than half of all known forms of life)—not to mention the myriad types of single-celled organisms. Researchers identify thousands of additional species each year. Estimates of the total number of species range from about 10 million to over 100 million. Whatever the actual number, the enormous variety of life gives biology a very broad scope. Biologists face a major challenge in attempting to make sense of this variety.

**Grouping Species: The Basic Idea**

There is a human tendency to group diverse items according to their similarities and their relationships to each other. For instance, we may speak of “squirrels” and “butterflies,” though we recognize that many different species belong to each group. We may even sort groups into broader categories, such as rodents (which include squirrels) and insects (which include butterflies). Taxonomy, the branch of biology that names and classifies species, formalizes this ordering of species into groups of increasing breadth, based on the degree to which they share characteristics (Figure 1.12). You will learn more about the details of this taxonomic scheme in Chapter 26. Here, we will focus on the big picture by considering the broadest units of classification, kingdoms and domains.
All the eukaryotes (organisms with eukaryotic cells) are now grouped in domain Eukarya. This domain includes three kingdoms of multicellular eukaryotes: kingdoms Plantae, 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, and animals obtain food by eating and digesting other organisms. Animalia is, of course, the kingdom to which we belong. But neither plants, nor fungi, nor animals are as numerous or diverse as the single-celled eukaryotes we call protists. Although protists were once placed in a single kingdom, recent evidence shows that some protists are more closely related to plants, animals, or fungi than they are to other protists. Thus, the recent taxonomic trend has been to split the protists into several kingdoms.
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, even among distantly related organisms (Figure 1.14).

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. It also introduces another important dimension of biology: historical time.

**Unity in the Diversity of Life**

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**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 1.15). 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.
Darwin’s second main point was his proposal that “natural selection” is an evolutionary mechanism for descent with modification.

Darwin developed his theory of natural selection from observations that by themselves were neither new nor profound. Others had described 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 that eat tough seeds as their major food source is that they have especially thick, strong beaks.

Making inferences from these three observations, Darwin arrived at his theory of evolution. He reasoned that individuals with inherited traits that are better suited to the local environment are more likely to survive and reproduce than less well-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.

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 1.16).

On the Origin of Species articulated two main points. The first point was that contemporary species arose from a succession of ancestors that differed from them. Darwin called this process “descent with modification.” This insightful phrase captured the duality of life’s unity and diversity—unity in the kinship among species that descended from common ancestors and diversity in the modifications that evolved as species branched from their common ancestors (Figure 1.17).
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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 1.20 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 many Galápagos organisms are clearly related to species on the South American mainland. After volcanoes built up 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. Years after Darwin collected the Galápagos finches, researchers began to sort out the relationships among these 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 the trees are often turned in Figure 1.18 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 1.19 are an excellent example of adaptation.

The Tree of Life

Take another look at the skeletal architecture of the bat’s wings in Figure 1.19. These wings are not like those of feathered birds; the bat is a mammal. The bat’s 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 foreleg of a horse, and the flipper of a whale. Indeed, all mammalian forelimbs are anatomical variations of a common architecture, much as the birds in Figure 1.17 are variations on an underlying “avian” 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

▲ Figure 1.18 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.

▲ Figure 1.19 Evolutionary adaptation. Bats, the only mammals capable of active flight, have wings with webbing between extended “fingers.” Darwin proposed that such adaptations are refined over time by natural selection.
sideways as in Figure 1.20. 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. Trace life back far enough, and we reach the early 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. Indeed, all of life is connected through its long evolutionary history.

Each branch point represents the common ancestor of the evolutionary lineages originating there and their descendants (to the right in this diagram).

▲ Figure 1.20 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 different food sources on the different islands. For example, among the seed-eaters, the heavier, thicker beaks are better at cracking larger seeds with strong coats, while the more slender beaks are better at picking up small seeds such as grass seeds.

CONCEPT CHECK 1.2

1. How is a mailing address analogous to biology’s hierarchical taxonomic system?
2. Explain why “editing” is an appropriate metaphor for how natural selection acts on a population’s heritable variation.
3. 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 Protista, 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.
Chapter 1  Evolution, the Themes of Biology, and Scientific Inquiry

volumes of quantitative data, such as the frequency and duration of specific behaviors for different members of a group of chimpanzees in a variety of situations. Quantitative data are generally expressed as numerical measurements and often organized into tables and graphs. Scientists analyze their data using a type of mathematics called statistics to test whether their results are significant or merely due to random fluctuations. (Note that all results presented in this text have been shown to be statistically significant.)

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.” Careful observations and data analyses, along with generalizations reached by induction, are fundamental to our understanding of nature.

Forming and Testing Hypotheses

Our innate curiosity often stimulates us to pose questions about the natural basis for the phenomena we observe in the world. What caused the different chimpanzee behaviors that Goodall observed in different situations? What causes the roots of a plant seedling to grow downward? In science, such inquiry usually involves the forming and testing of hypothetical explanations—that is, hypotheses.

In science, a hypothesis is a tentative answer to a well-framed question—an explanation on trial. It is usually a rational account for a set of observations, based on the available data and guided by inductive reasoning. A scientific hypothesis must lead to predictions that can be tested by

CONCEPT 1.3

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

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. The word science is derived from a Latin verb meaning “to know.” Striving to understand seems to be one of our basic urges.

At the heart of science is inquiry, a search for information and explanations of natural phenomena. There is no formula for successful scientific inquiry, no single scientific method that researchers must rigidly follow. As in all quests, science includes elements of challenge, adventure, and luck, along with careful planning, reasoning, creativity, 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 highlight certain characteristics that help to distinguish science from other ways of describing and explaining nature.

Scientists use a process of inquiry that includes making observations, forming logical, testable explanations (hypotheses), and testing them. The process is necessarily repetitive: In testing a hypothesis, more observations may inspire revision of the original hypothesis or formation of a new one, thus leading to 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. Observation is the gathering of information, either through direct use of the senses or with the help of tools such as microscopes, thermometers, and balances that extend our senses. Observations can reveal valuable information about the natural world. For example, a series of detailed observations have shaped our understanding of cell structure, and another set of observations is currently expanding our databases of genomes of diverse species and of genes whose expression is altered in cancer and other diseases.

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 1.21). Along with these qualitative data, Goodall also enriched the field of animal behavior with
making additional observations or by performing experiments. An experiment is a scientific test, carried out under controlled conditions.

We all use observations and develop questions and hypotheses in solving everyday problems. Let’s say, for example, that your flashlight fails while you are camping. 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 informal experiments. For example, the dead-battery hypothesis predicts that replacing the batteries will fix the problem.

Figure 1.22 diagrams this campground inquiry. Figuring things out like this, by systematic trial and error, is a hypothesis-based approach.

Sometimes we can’t carry out an experiment but can test a hypothesis using observations. Let’s say you don’t have a spare bulb or spare batteries. How could you figure out which hypothesis is more likely? You could examine the bulb and see if it looks burnt out. You could also check the expiration date on the battery. Experiments are great ways to test hypotheses, but when experiments aren’t possible, we can often test a hypothesis in other ways.

**Deductive Reasoning**

A type of logic called deduction is also built into the use of hypotheses in science. While induction entails reasoning from a set of specific observations to reach a general conclusion, **deductive reasoning** 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. In the scientific process, deductions usually take the form of predictions of results that will be found if a particular hypothesis (premise) is correct. We then test the hypothesis by carrying out 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, then the flashlight should work if you replace the batteries with new ones.

The flashlight inquiry demonstrates two other key points about the use of hypotheses in science. First, the initial observations may give rise to multiple hypotheses. The ideal plan is to design experiments to test all these candidate explanations. For instance, another of the many possible alternative hypotheses to explain our dead flashlight is that both the batteries and the bulb are bad, and you could design an experiment to test this.

Second, we can never prove that a hypothesis is true. Based on the experiments shown in Figure 1.22, the burnt-out bulb hypothesis stands out as the most likely explanation. The results support that hypothesis but do not absolutely prove it is correct. 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 test the burnt-out bulb hypothesis again by trying another experiment—removing the original bulb and carefully reinstalling it. If the flashlight still doesn’t work, the burnt-out bulb hypothesis is supported by another line of evidence—but still not proven. For example, the bulb may have another defect not related to being burnt out. Testing a hypothesis in various ways, producing different sorts of data, can increase our confidence in it tremendously, but no amount of experimental testing can prove a hypothesis beyond a shadow of doubt.

**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. A scientific hypothesis must be testable; there must be some observation or experiment that could reveal if such an idea is likely to be true or false. The hypothesis that dead batteries are the sole cause of the broken flashlight could be (and was) tested by replacing the old batteries with new ones.

Not all hypotheses meet the criteria of science: You wouldn’t be able to test the hypothesis that invisible campground ghosts are fooling with your flashlight! Because science only deals with natural, testable explanations for natural phenomena, it can neither support nor contradict the invisible ghost hypothesis, nor whether spirits, elves, or fairies, either benevolent or evil, cause storms, rainbows, illnesses, and cures. Such supernatural explanations, because
they cannot be tested, are simply outside the bounds of science. For the same reason, science does not deal with religious matters, which are issues of personal faith. Science and religion are not mutually exclusive or contradictory, they are simply concerned with different issues.

The Flexibility of the Scientific Process

The flashlight example of Figure 1.22 traces an idealized process of inquiry sometimes 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, which is often applied in hindsight, after the experiment or study is completed. For example, a scientist may start to design an experiment, but then backtrack after 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. Science is a lot more unpredictable—and exciting—than lock-step adherence to any five-step method.

A more realistic model of the scientific process is shown in Figure 1.23. The core activity (the central circle in the
testing hypotheses and interpreting data are at the heart of science, these pursuits represent only part of the picture.

A Case Study in Scientific Inquiry: Investigating Coat Coloration in Mouse 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. Color patterns of animals vary widely in nature, sometimes even among members of the same species. What accounts for such variation? An illustrative example is found in two populations of mice that belong to the same species (*Peromyscus polionotus*) but have different color patterns and reside in different environments (Figure 1.24). The beach mouse lives along the Florida seashore, a habitat of brilliant white sand dunes with sparse clumps of beach grass. The inland mouse lives on darker, more fertile soil farther inland. Even a brief glance at the photographs in Figure 1.24 reveals a striking match of mouse coloration to its habitat. The natural predators of these mice, including hawks, owls, foxes, and coyotes, are all visual hunters.
eyes to look for prey). It was logical, therefore, for Francis Bertody Sumner, a naturalist studying populations of these mice in the 1920s, to form the hypothesis that their coloration patterns had evolved as adaptations that camouflage the mice in their native environments, protecting them from predation.

As obvious as the camouflage hypothesis may seem, it still required testing. In 2010, biologist Hopi Hoekstra of Harvard University and a group of her students headed to Florida to test the prediction that mice with coloration that did not match their habitat would be preyed on more heavily than the native, well-matched mice. Figure 1.25 summarizes this field experiment.

The researchers built hundreds of plasticine models of mice and spray-painted them to resemble either beach mice (light colored) or inland mice (darker colored), so that the models differed only in their color patterns. The researchers placed equal numbers of these model mice randomly in both habitats and left them overnight. The mouse models resembling the native mice in the habitat were the control group (for instance, light-colored beach mouse models in the beach habitat), while the mouse models with the non-native coloration were the experimental group (for example, darker-colored inland mouse models in the beach habitat). The following morning, the team counted and recorded signs of predation events, which ranged from bites and gouge marks on some models to the outright disappearance of others. Judging by the shape of the predator’s bites and the tracks surrounding the experimental sites, the predators appeared to be split fairly evenly between mammals (such as foxes and coyotes) and birds (such as owls, herons, and hawks).

For each environment, the researchers then calculated the percentage of predation events that targeted camouflaged mouse models. The results were clear: Camouflaged models experienced much less predation than those lacking camouflage in both the beach habitat (where light mice were less vulnerable) and the inland habitat (where dark mice were less vulnerable). The data thus fit the key prediction of the camouflage hypothesis. For more information about Hopi Hoekstra and her research with beach mice, see the interview before Chapter 22.

### Figure 1.25 Inquiry

**Does camouflage affect predation rates on two populations of mice?**

**Experiment** Hopi Hoekstra and colleagues wanted to test the hypothesis that coloration of beach and inland mice (*Peromyscus polionotus*) provides camouflage that protects them from predation in their respective habitats. The researchers spray-painted mouse models with either light or dark color patterns that matched those of the beach and inland mice and then placed models with both patterns in each of the habitats. The next morning, they counted damaged or missing models.

**Results** For each habitat, the researchers calculated the percentage of attacked models that were camouflaged or non-camouflaged. In both habitats, the models whose pattern did not match their surroundings suffered much higher “predation” than did the camouflaged models.

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Percentage of Attacked Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach habitat</td>
<td></td>
</tr>
<tr>
<td>Camouflaged</td>
<td>Non-camouflaged</td>
</tr>
<tr>
<td>Light models</td>
<td>Dark models</td>
</tr>
<tr>
<td>Non-camouflaged</td>
<td>Camouflaged (control)</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Inland habitat</td>
<td></td>
</tr>
<tr>
<td>Camouflaged</td>
<td>Non-camouflaged</td>
</tr>
<tr>
<td>Light models</td>
<td>Dark models</td>
</tr>
<tr>
<td>Non-camouflaged</td>
<td>Camouflaged (control)</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

**Conclusion** The results are consistent with the researchers’ prediction: that mouse models with camouflage coloration would be preyed on less often than non-camouflaged mouse models. Thus, the experiment supports the camouflage hypothesis.


**Interpret the Data** The bars indicate the percentage of the attacked models that were either light or dark. Assume 100 mouse models were attacked in each habitat. For the beach habitat, how many were light models? Dark models? Answer the same questions for the inland habitat.

### Experimental Variables and Controls

Earlier in this section, we described an experiment as a scientific test carried out under controlled conditions. More specifically, an experiment involves manipulation of one factor in a system in order to see the effects of changing it. Both the factor that is manipulated and the effects that are measured are types of experimental variables—factors that vary in an experiment.

The mouse camouflage experiment described in Figure 1.25 is an example of a controlled experiment, one that is designed to compare an experimental group (the non-camouflaged mice, in this case) with a control group (the camouflaged mice normally resident in the area). Ideally, the experimental and control groups are designed to differ only in the one factor the experiment is testing—in our example, the effect of mouse coloration on the behavior of predators. Here, mouse color is the factor manipulated by
chapter 1

Theories in Science

Our everyday use of the term theory often implies an untested speculation: “It’s just a theory!” 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: “Fur coloration well-matched to their habitat is an adaptation that protects mice from predators.” But this is a theory: “Evolutionary adaptations arise by natural selection.” This theory proposes that natural selection is the evolutionary mechanism that accounts for an enormous variety of adaptations, of which coat color in mice is but one example.

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 the Chapter 23 overview.)

And third, compared with any hypothesis, a theory is generally supported by a much greater body of evidence. The theory of natural selection has been supported by a vast quantity of evidence, with more being found every day, and has not been contradicted by any scientific data. Other similarly supported theories include the theory of gravity and the theory that the Earth revolves around the sun. Those theories that become widely adopted in science explain a great range of observations and are supported by a vast accumulation of evidence. In fact, scrutiny of theories continues through testing of the specific hypotheses they generate.

In spite of the body of evidence supporting a widely accepted theory, scientists will modify or even reject theories when new research produces 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 at best conditional, based on the preponderance of available evidence.

CONCEPT CHECK 1.3

1. Contrast inductive reasoning with deductive reasoning.
2. In the mouse camouflage experiment, what is the independent variable? The dependent variable? Explain.
3. Why is natural selection called a theory?
4. WHAT IF? In the deserts of the southwestern United States, the soils are mostly sandy, with occasional large regions of black rock derived from lava flows that occurred 1.7 million years ago. Mice are found in both sandy and rocky areas, and owls are known predators. What might you expect about coat color in these two mouse populations? Explain. How would you use this ecosystem to further test the camouflage hypothesis?

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. 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 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. In fact, Hopi Hoekstra’s experiment benefited from the work of another researcher, D. W. Kaufman, 40 years earlier. You
**INTERPRETING A PAIR OF BAR GRAPHS**

**How Much Does Camouflage Affect Predation on Mice by Owls with and without Moonlight?** D. W. Kaufman investigated the effect of prey camouflage on predation. Kaufman tested the hypothesis that the amount of contrast between the coat color of a mouse and the color of its surroundings would affect the rate of nighttime predation by owls. He also hypothesized that the color contrast would be affected by the amount of moonlight. In this exercise, you will analyze data from his owl-mouse predation studies.

**How the Experiment Was Done** Pairs of mice (Peromyscus polionotus) with different coat colors, one light brown and one dark brown, were released simultaneously into an enclosure that contained a hungry owl. The researcher noted the color of the mouse that was first caught by the owl. If the owl did not catch either mouse within 15 minutes, the test was recorded as a zero. The release trials were repeated multiple times in enclosures with either a dark-colored soil surface or a light-colored soil surface. The presence or absence of moonlight during each trial was recorded.

**Data from the Experiment**

<table>
<thead>
<tr>
<th>Number of mice caught</th>
<th>Light coat</th>
<th>Dark coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full moon</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>No moon</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

**Interpret the Data**

1. First, make sure you understand how the graphs are set up. Graph A shows data from the light-colored soil enclosure and graph B from the dark-colored enclosure, but in all other respects the graphs are the same. (a) There is more than one independent variable in these graphs. What are the independent variables, the variables that were tested by the researcher? Which axis of the graphs has the independent variables? (b) What is the dependent variable, the response to the variables being tested? Which axis of the graphs has the dependent variable?

2. (a) How many dark brown mice were caught in the light-colored soil enclosure on a moonlit night? (b) How many dark brown mice were caught in the dark-colored soil enclosure on a moonlit night? (c) On a moonlit night, would a dark brown mouse be more likely to escape predation by owls on dark- or light-colored soil? Explain your answer.

3. (a) Is a dark brown mouse on dark-colored soil more likely to escape predation under a full moon or with no moon? (b) A light brown mouse on light-colored soil? Explain.

4. (a) Under which conditions would a dark brown mouse be most likely to escape predation at night? (b) A light brown mouse?

5. (a) What combination of independent variables led to the highest predation level in enclosures with light-colored soil? (b) What combination of independent variables led to the highest predation level in enclosures with dark-colored soil? (c) What relationship, if any, do you see in your answers to parts (a) and (b)?

6. What conditions are most deadly for both light brown and dark brown mice?

7. Combining the data shown in both graphs, estimate the total number of mice caught in moonlight versus no-moonlight conditions. Which condition is optimal for predation by the owl on mice? Explain your answer.


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**SCIENTIFIC SKILLS EXERCISE**

Interpreting a Pair of Bar Graphs

How Much Does Camouflage Affect Predation on Mice by Owls with and without Moonlight? D. W. Kaufman investigated the effect of prey camouflage on predation. Kaufman tested the hypothesis that the amount of contrast between the coat color of a mouse and the color of its surroundings would affect the rate of nighttime predation by owls. He also hypothesized that the color contrast would be affected by the amount of moonlight. In this exercise, you will analyze data from his owl-mouse predation studies.

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Data from the Experiment

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A version of this Scientific Skills Exercise can be assigned in MasteringBiology.


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can study the design of Kaufman’s experiment and interpret the results in the Scientific Skills Exercise.

Scientific results are continually vetted through the repetition of observations and experiments. 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.

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 species are evolutionarily related, such an organism may be viewed as a model for understanding the biology of other species and their diseases. For example, genetic studies of the fruit fly Drosophila melanogaster have taught us a lot about how genes work in other species, even 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 approach interesting questions from different angles. Some biologists focus on ecosystems, while others study natural phenomena at the level of organisms or cells. This text is divided into units that look at biology at different levels. Yet any given problem can be addressed from many perspectives, which in fact complement each other. For example, Hoekstra’s work uncovered at least one genetic mutation that underlies the differences between beach and inland mouse coloration. Her lab includes biologists specializing at different biological levels, allowing links to be made between the evolutionary adaptations she focuses on and their molecular basis in DNA sequences.

As a biology student, you can benefit from making connections between the different levels of biology. You can 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. Sickle-cell disease will appear in several units of the text, each time addressed at a new level. In addition, we have designed a number of figures that make connections between the content in different chapters, as well as questions that ask you to make the connections yourselves. We hope these features will help you integrate the material you’re learning and enhance your enjoyment of biology by encouraging you to keep the big picture in mind.

Science, Technology, and Society

The research community is part of society at large, and the relationship of science to society becomes clearer when we add technology to the picture (see Figure 1.23). Though science and technology sometimes employ similar inquiry patterns, their basic goals differ. The goal of science is to understand natural phenomena, while that of technology is to apply scientific knowledge for some specific purpose. Biologists and other scientists usually speak of “discoveries,” while engineers and other technologists more often speak of “inventions.” Because scientists put new technology to work in their research, 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 1.26). 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.

Ethical issues raised by such questions 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 the society around it. 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 text welcome all students to the community of biologists, wishing you the joys and satisfactions of this exciting field of science.

**CONCEPT CHECK 1.4**

1. How does science differ from technology?
2. **MAKE CONNECTIONS** The gene that causes sickle-cell disease is present in a higher percentage of residents of sub-Saharan Africa than among those of African descent living in the United States. 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. (See Concept 1.2.)

For suggested answers, see Appendix A.
Interactions Theme: From Ecosystems to Molecules, Interactions Are Important in Biological Systems

- Organisms interact continuously with physical factors. Plants take up nutrients from the soil and chemicals from the air and use energy from the sun. Interactions among plants, animals, and other organisms affect the participants in various ways.

- In feedback regulation, a process is regulated by its output or end product. In negative feedback, accumulation of the end product slows its production. In positive feedback, an end product speeds up its own production. Feedback is a type of regulation common to life at all levels, from molecules to ecosystems.

Evolution, the Core Theme of Biology

- Evolution, the process of change that has transformed life on Earth, accounts for the unity and diversity of life. It also explains evolutionary adaptation—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. 10–15)

- 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 parachute-like structure carrying a seed shown on the first page of this chapter?

Concept 1.3

In studying nature, scientists make observations and form and test hypotheses (pp. 16–21)

- 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. Hypotheses must be testable; science can address neither the possibility of supernatural phenomena nor the validity of religious beliefs. Hypotheses can be tested by experimentation or, when that is not possible, by making observations. In the process of science, the core activity is testing ideas. This endeavor is influenced by three arenas: exploration and discovery, community analysis and feedback, and societal benefits and outcomes. Testing ideas, in turn, affects each of these three pursuits as well.
- Controlled experiments, such as the study investigating coat coloration in mouse 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 gathering and interpreting data in the process of scientific inquiry?

Concept 1.4

Science benefits from a cooperative approach and diverse viewpoints (pp. 21–24)

- 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 consists of any 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. 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. organism, brain, organ system, nerve cell
   b. organ system, nervous tissue, brain, nerve cell
   c. organism, organ system, tissue, cell, organ
   d. nervous system, brain, nervous tissue, nerve cell
Level 3: Synthesis/Evaluation

12. Evolution Connection
A typical prokaryotic cell has about 3,000 genes in its DNA, while a human cell has almost 21,000 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 1,000 genes. What sorts of functions might these shared genes have?

13. Scientific Inquiry
Based on the results of the mouse coloration case study, suggest another hypothesis researchers might use to further study the role of predators in the natural selection process.

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 a suggested grading rubric and tips for writing good essays in the Study Area of MasteringBiology under “Write About a Theme.”)

15. Synthesize Your Knowledge

Can you pick out the mossy leaf-tailed gecko lying against the tree trunk in this photo? How is the appearance of the gecko a benefit in terms of survival? Given what you learned about evolution, natural selection, and genetic information in this chapter, describe how the gecko’s coloration might have evolved.

For selected answers, see Appendix A.

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