Introduction: Themes in the Study of Life

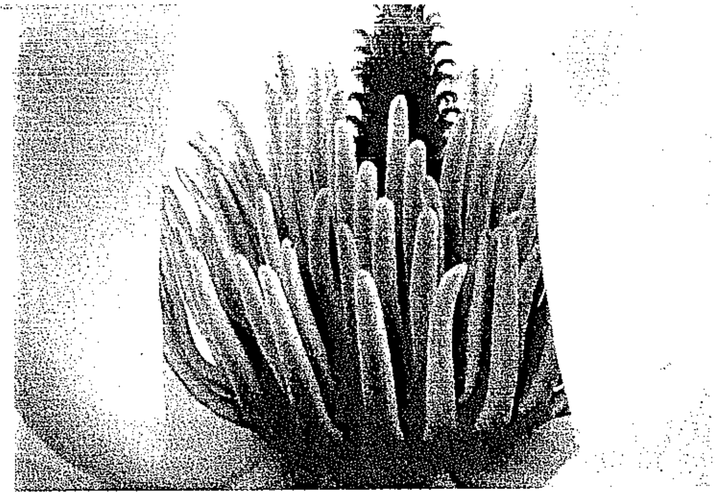


Figure 1.1 What properties of life are demonstrated by this flower?

KEY CONCEPTS

- **1.1** **Themes connect the concepts of biology**
- **1.2** ***The Core Theme:*** **Evolution accounts for the unity and diversity of life**
- **1.3** **Scientists use two main forms of inquiry in their study of nature**

OVERVIEW

Inquiring About the World of Life

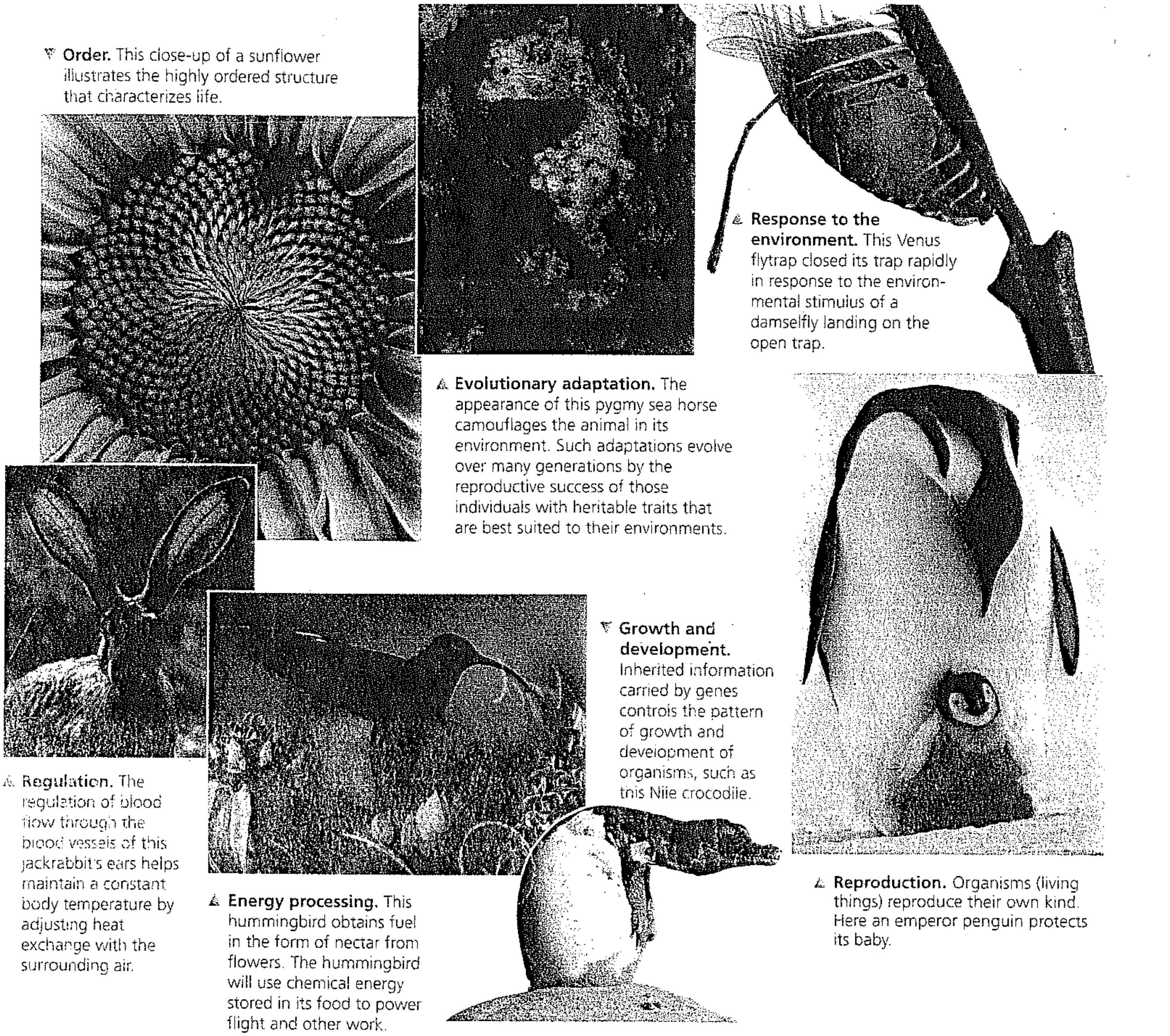
The flower featured on the cover of this book and in **Figure 1.1** is from a magnolia, a tree of ancient lineage that is native to Asian and American forests. The magnolia blossom is a sign of the plant's status as a living organism, for flowers contain organs of sexual reproduction, and reproduction is a key property of life, as you will learn later.

Like all organisms, the magnolia tree in **Figure 1.2** is living in close association with other organisms, though it is a lone specimen far from its ancestral forest. For example, it depends on beetles to carry pollen from one flower to another, and the beetles, in turn, eat from its flowers. The flowers are adapted to the beetles in several ways: Their bowl shape allows easy access, and their multiple reproductive organs and tough petals (see Figure 1.1) help ensure that some survive the voracious beetles. Such adaptations 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. As discussed later in this chapter, evolution is the fundamental organizing principle of biology and the main theme of this book.

Although biologists know a great deal about magnolias and other plants, many mysteries remain. For instance, what exactly led to the origin of flowering plants? 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. Can you think of some questions about living organisms that interest you? When you do, you are already starting to think like a biologist. More than anything else, biology is a quest, an ongoing inquiry about the nature of life.

Perhaps some of your questions relate to health or to societal or environmental issues. Biology is woven into the fabric of our culture more than ever before and can help answer many questions that affect our lives. Research breakthroughs in genetics and cell biology are transforming medicine and agriculture. Neuroscience and evolutionary biology are reshaping psychology and sociology. New models in ecology are helping societies evaluate environmental issues, such as global warming. There has never been a more important time to embark on a study of life.

Figure 1.2 A magnolia tree in early spring.



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

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.

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.

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

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.

Reproduction. Organisms (living things) reproduce their own kind. Here an emperor penguin protects its baby.

Figure 1.3 Some properties of life.

Is a gasoline-powered lawn mower alive? Which of these properties does it have? Which properties does it lack?

But what is life? Even a small child realizes that a dog or a plant is alive, while a rock 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** 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 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 overarching theme, evolution, with an introduction to the reasoning that led Charles Darwin to his explanatory theory. Finally, we look at scientific inquiry—how scientists raise and attempt to answer questions about the natural world.

Themes connect the concepts of biology

Biology is a subject of enormous scope, and anyone who follows the news knows that biological knowledge is expanding at an ever-increasing rate. Simply memorizing the factual details of this huge subject is not a reasonable option. How, then, can you, as a student, go beyond the facts to develop a coherent view of life? One approach is to fit the many things you learn into a set of themes that pervade all of biology—ways of thinking about life that will still apply decades from now. Focusing on a few big ideas will help you organize and make sense of all the information you'll encounter as you study biology. To help you, we have selected seven unifying themes to serve as touchstones as you proceed through this book.

Evolution, the Overarching Theme of Biology

Evolution is biology's core theme—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 penguins 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 to 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. We'll return to evolution later in the chapter, after surveying some other themes and painting a fuller picture of the scope of biology.

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, and our destination is a forest in Ontario, Canada, 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 circled 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, if you make a test-tube mixture of chlorophyll and all the other kinds of molecules found in a chloroplast, photosynthesis will not occur. Photosynthesis can take place only when the molecules are arranged in a specific way in an intact chloroplast. To take another example, if a serious head injury disrupts the intricate architecture of a human brain, the mind may cease to function properly even though all of the brain parts 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.

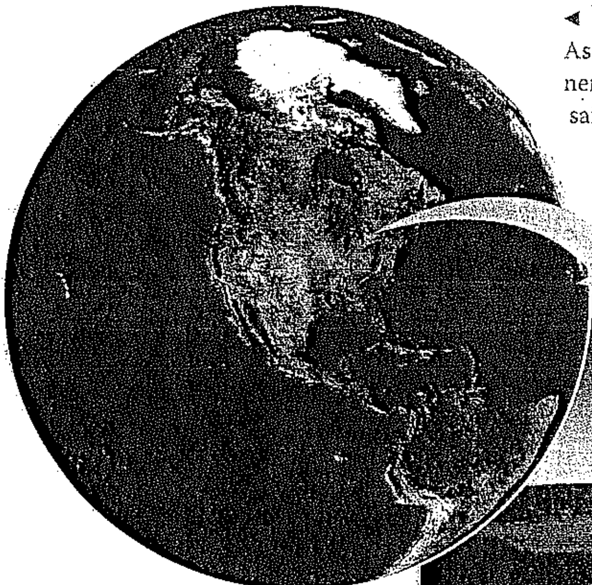
Emergent properties are not unique to life. We can see the importance of arrangement in the distinction between a box of bicycle parts and a working bicycle. And while graphite and diamonds are both pure carbon, they have very different properties because their carbon atoms are arranged differently. But compared to such nonliving examples, 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 reduction of 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. At the cutting edge of research today is the approach called systems biology.

Exploring Levels of Biological Organization



1 The Biosphere

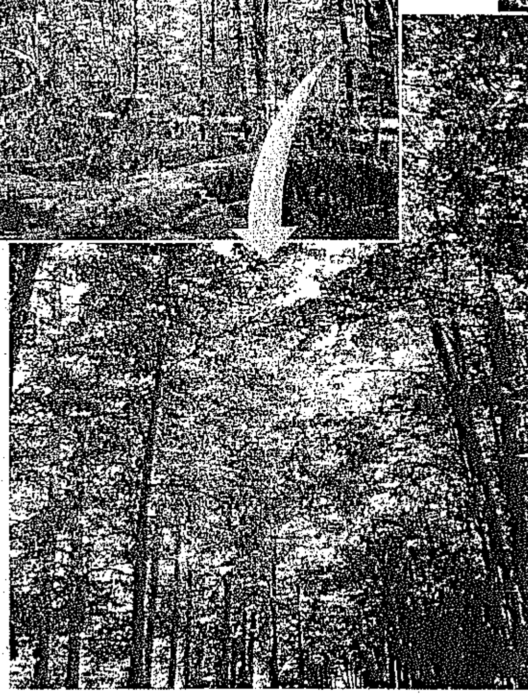
As soon as we are near enough to Earth to make out its continents and oceans, we begin to see signs of life—in the green mosaic of the planet's forests, for example. This is our first view of the biosphere, which consists of all the environments on Earth that are inhabited by life. The biosphere includes most regions of land, most bodies of water, and the atmosphere to an altitude of several kilometers.

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 deciduous trees (trees that lose their leaves in one season and grow new ones in another). 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

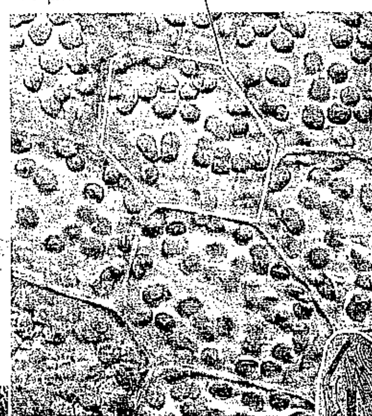
Individual living things are called organisms. Each of the maple trees and other plants in the forest is an organism, and so is each forest animal, such as a frog, squirrel, deer, and beetle. The soil teems with microorganisms such as bacteria.

▼ 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 consisting of two or more tissues (which we'll see upon our next scale change). An organ 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 specific function. For example, the human digestive system includes such organs as the tongue, stomach, and intestines.

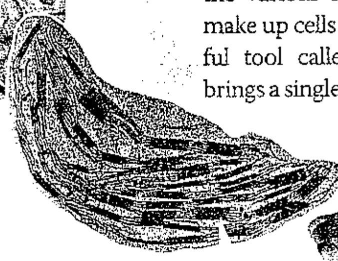
▼ 8 Cells

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 below, we see a more highly magnified view of some of the cells in a leaf tissue. Each of the cells is only about 25 micrometers (μm) across. It would take more than 700 of these cells to reach across a penny. As small as these cells are, you can see that each contains numerous green structures called chloroplasts, which are responsible for photosynthesis.



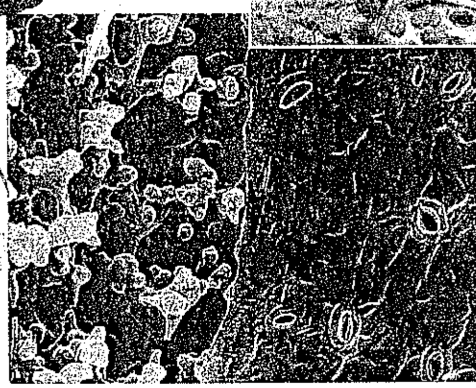
▼ 9 Organelles

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



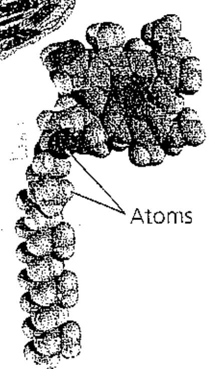
▶ 7 Tissues

Our next scale change—to see a leaf's tissues—requires a microscope. 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 tissue called epidermis, the "skin" on the surface of the leaf (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 cellular structure. In fact, each kind of tissue is a group of similar cells.



▶ 10 Molecules

Our last scale change vaults 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 chlorophylls and other molecules are organized into the equipment that converts light energy to the chemical energy of food.



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 ecosytem. 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 changing perspective is analogous to moving from ground level on a street corner 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.

The goal of **systems biology** is to construct models for the dynamic behavior of whole biological systems. 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 functions 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 big questions like the last one.

Systems biology is relevant to the study of life at all levels. During the early years of the 20th century, biologists studying animal physiology (functioning) 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. Such models have already been useful for predicting the responses of these systems to changing variables. More recently, systems biology has taken hold at the cellular and molecular levels, as we'll describe later when we discuss DNA.

Theme: Organisms interact with their environments, exchanging matter and energy

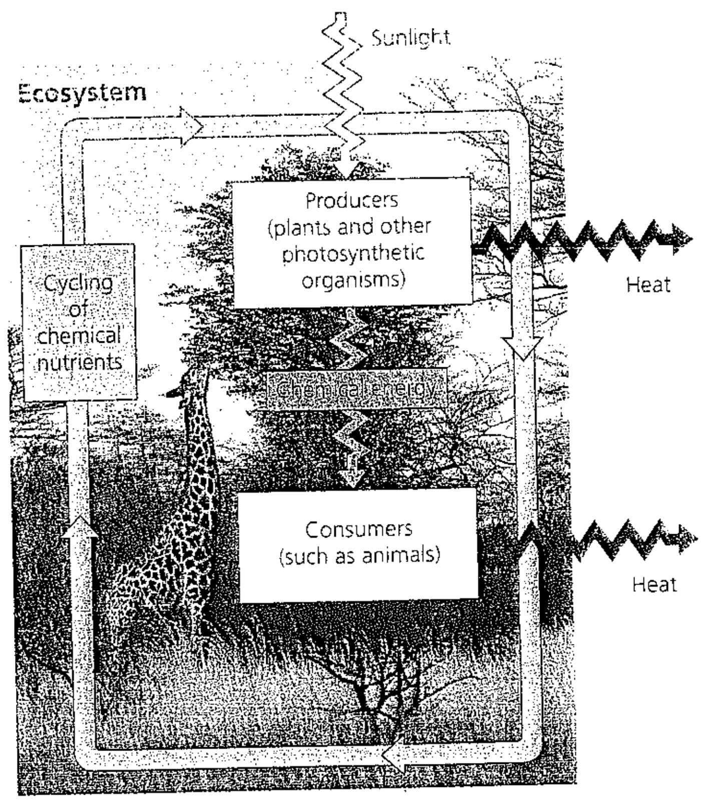
Turn back again to Figure 1.4, this time focusing on the forest. In this or any other ecosystem, each organism interacts continuously with its environment, which includes both nonliving factors and other organisms. A tree, for example, absorbs water and minerals from the soil, through its roots. At the same time, its leaves take in carbon dioxide from the air and use sunlight absorbed by chlorophyll to drive photosynthesis, converting water and carbon dioxide to sugar and oxygen. The tree releases oxygen to the air, and its roots help form soil by breaking up rocks. Both organism and environment are affected by the interactions between them. The tree also interacts with other organisms, such as soil microorganisms associated with its roots and animals that eat its leaves and fruit.

Ecosystem Dynamics

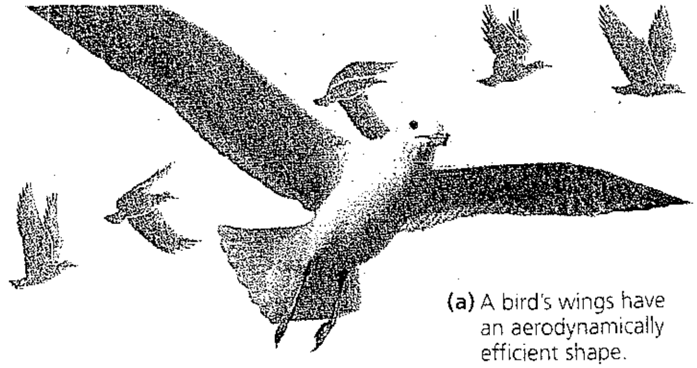
The operation of any ecosystem involves two major processes. One process is the cycling of nutrients. For example, minerals acquired by a tree will eventually be returned to the soil by organisms that decompose leaf litter, dead roots, and other organic debris. The second major process in an ecosystem is the one-way flow of energy from sunlight to producers to consumers. Producers are plants and other photosynthetic organisms, which use light energy to make sugar. Consumers are organisms, such as animals, that feed on producers and other consumers. The diagram in **Figure 1.5** outlines the two processes acting in an African ecosystem.

Energy Conversion

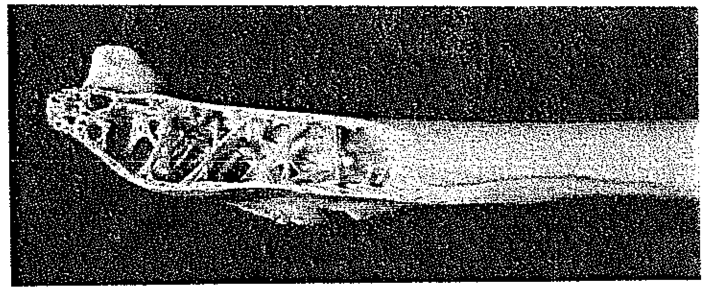
Moving, growing, reproducing, and the other activities of life are work, and work requires energy. The exchange of energy between an organism and its surroundings often involves the transformation of one form of energy to another. For example, the leaves of a plant absorb light energy and convert it to chemical energy stored in sugar molecules. When an animal's muscle cells use sugar as fuel to power movements, they convert chemical energy to kinetic energy, the energy of motion. And



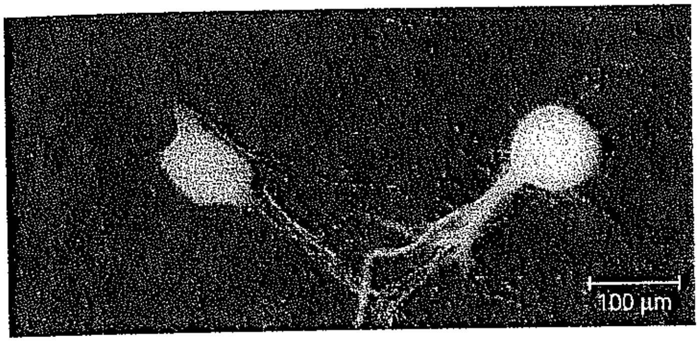
▲ **Figure 1.5 Nutrient cycling and energy flow in an ecosystem.**



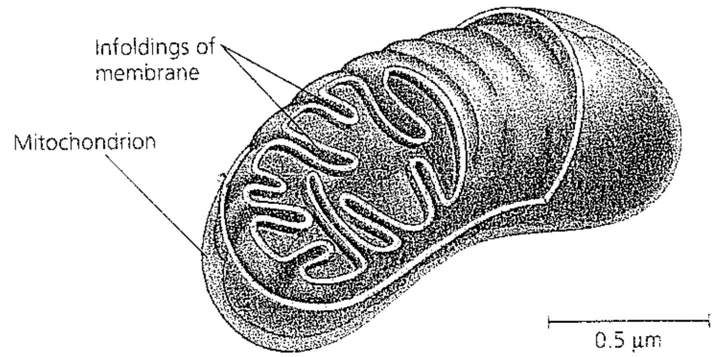
(a) A bird's wings have an aerodynamically efficient shape.



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



(c) The flight muscles are controlled by neurons (nerve cells), which transmit signals. With long extensions, neurons are especially well structured for communication within the body.



(d) The flight muscles obtain energy in a usable form from organelles called mitochondria. A mitochondrion has an inner membrane with many infoldings. Molecules embedded in the inner membrane carry out many of the steps in energy production, and the infoldings pack a large amount of this membrane into a small container.

▲ **Figure 1.6 Form fits function in a gull's wing.** A bird's build and the structures of its components make flight possible.

How does form fit function in a human hand?

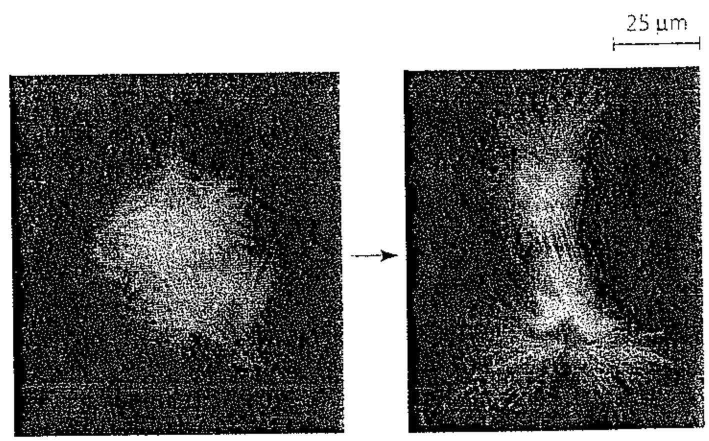
in all these energy conversions, some of the energy is converted to thermal energy, which dissipates to the surroundings as heat. In contrast to chemical nutrients, which recycle within an ecosystem, energy flows through an ecosystem, usually entering as light and exiting as heat (see Figure 1.5).

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 1.6**). In exploring life on its different structural levels, we discover functional beauty at every turn.

Theme: Cells are an organism's basic units 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 division of cells to form new cells is the basis for all reproduction and for the growth and repair of multicellular organisms (**Figure 1.7**). To

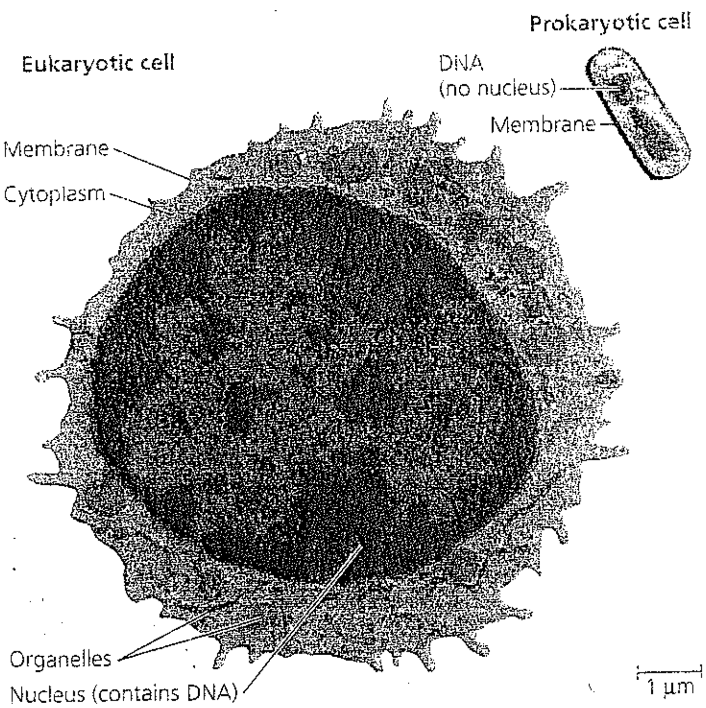


▲ **Figure 1.7 A lung cell from a newt divides into two smaller cells that will grow and divide again.**

cite another example, 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 and archaea 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, such as the ones you see in **Figure 1.8** and the chloroplast you saw in Figure 1.4. 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. As Figure 1.8 also shows, prokaryotic cells are much simpler and generally smaller than eukaryotic cells. 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. But whether an organism has prokaryotic or eukaryotic cells, its structure and function depend on cells.



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

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

Inside the dividing cell in Figure 1.7 (on the previous page), 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

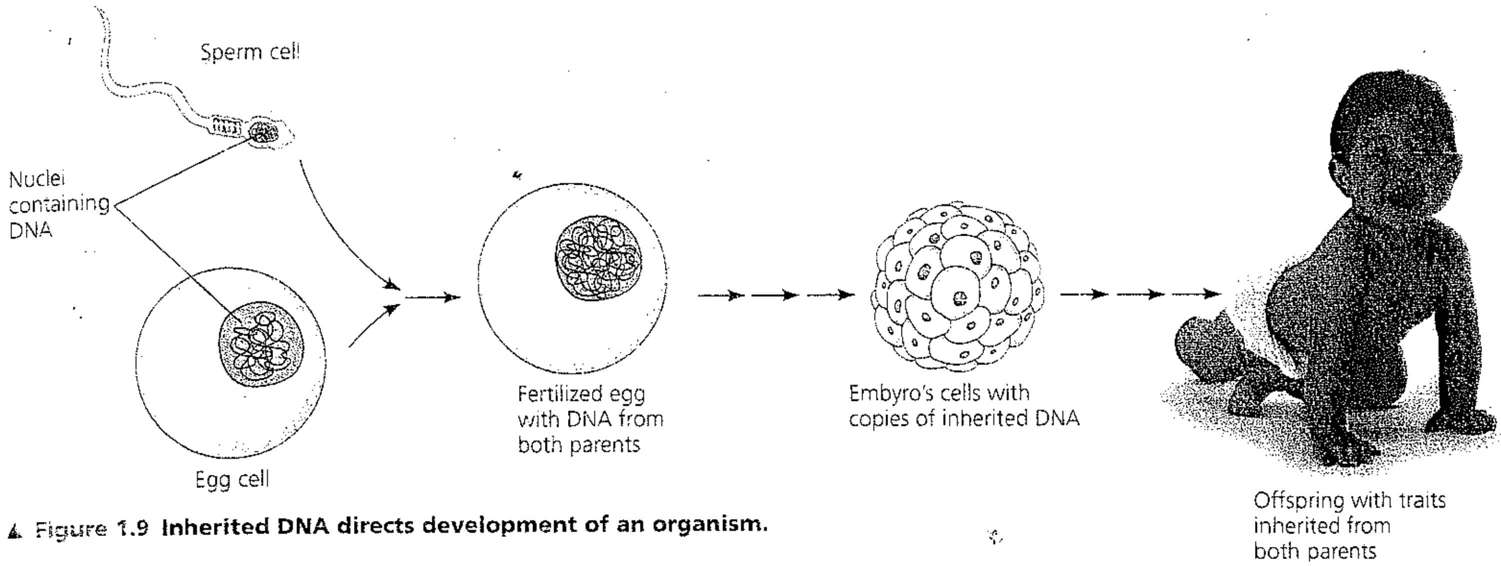
Each chromosome has one very long DNA molecule, with hundreds or thousands of genes arranged along its length. The DNA of chromosomes replicates as a cell prepares to divide, and each of the two cellular offspring inherits a complete set of genes.

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 it to our trillions of cells. In each cell, the genes along the length of the DNA molecules encode the information for building the cell's other molecules. In this way, DNA controls the development and maintenance of the entire organism and, indirectly, everything it does **(Figure 1.9)**. The DNA serves as a central database.

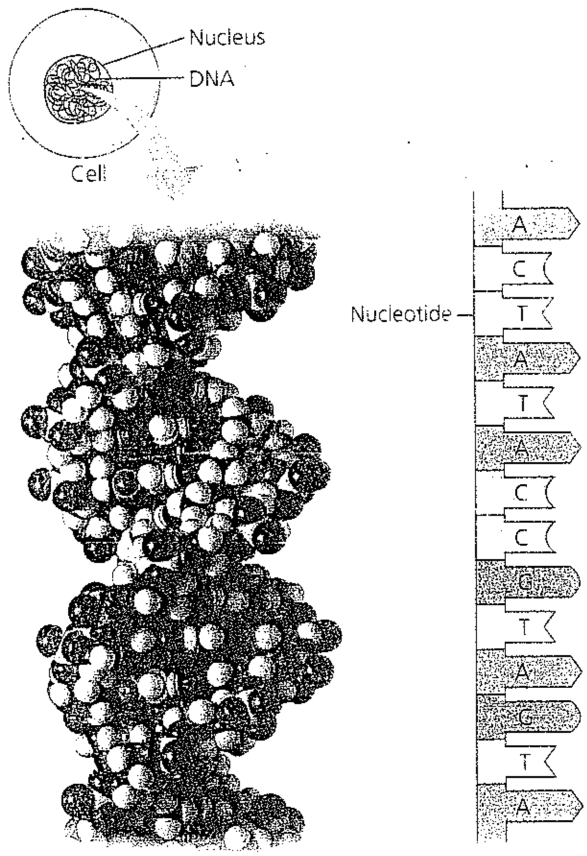
The molecular structure of DNA accounts for its ability to store information. Each DNA molecule is made up of two long chains arranged in a double helix. Each chain link is one of four kinds of chemical building blocks called nucleotides **(Figure 1.10)**. The way DNA encodes information is analogous to the way 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. Libraries are filled with books containing information encoded in varying sequences of only 26 letters. We can think of nucleotides as the alphabet of inheritance. Specific sequential arrangements of these four chemical letters encode the precise information in genes, which are typically hundreds or thousands of nucleotides long. One gene in a bacterial cell may be translated as "Build a certain component of the cell membrane." A particular human gene may mean "Make growth hormone."

More generally, genes like those just mentioned program the cell's production of large molecules called proteins. Other human proteins include a muscle cell's contraction proteins and the defensive proteins called antibodies. A class of proteins crucial to all cells are enzymes, which catalyze (speed up) specific chemical reactions. Thus, DNA provides the blueprints, and proteins serve as the tools that actually build and maintain the cell and carry out its activities.

The DNA of genes controls protein production indirectly, using a related kind of molecule called RNA as an intermediary.



▲ **Figure 1.9 Inherited DNA directs development of an organism.**



(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 here as A, T, C, and G.)

▲ **Figure 1.10 DNA: The genetic material.**

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. In the translation process, all forms of life employ essentially the same genetic code. A particular sequence of nucleotides says the same thing to one organism as it does to another. Differences between organisms reflect differences between their nucleotide sequences.

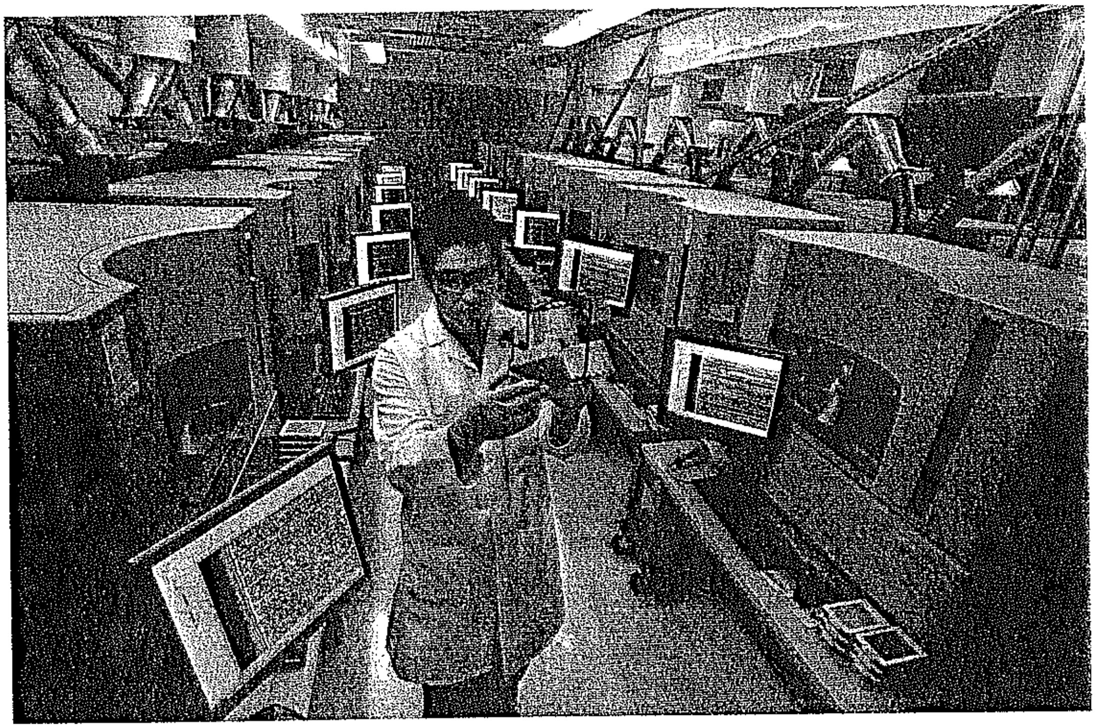
Not all RNA in the cell is translated into protein. We have known for decades that some types of RNA molecules are actually components of the cellular machinery that manufactures proteins. Recently, scientists have discovered whole new classes of RNA that play other roles in the cell, such as regulating the functioning of protein-coding genes.

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 nucleotides. If the one-letter symbols for these nucleotides 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.

Systems Biology at the Levels of Cells and Molecules

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 animals. These accomplishments have been made possible by the development of new methods and DNA-sequencing machines, such as those shown in **Figure 1.11**, on the next page.

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



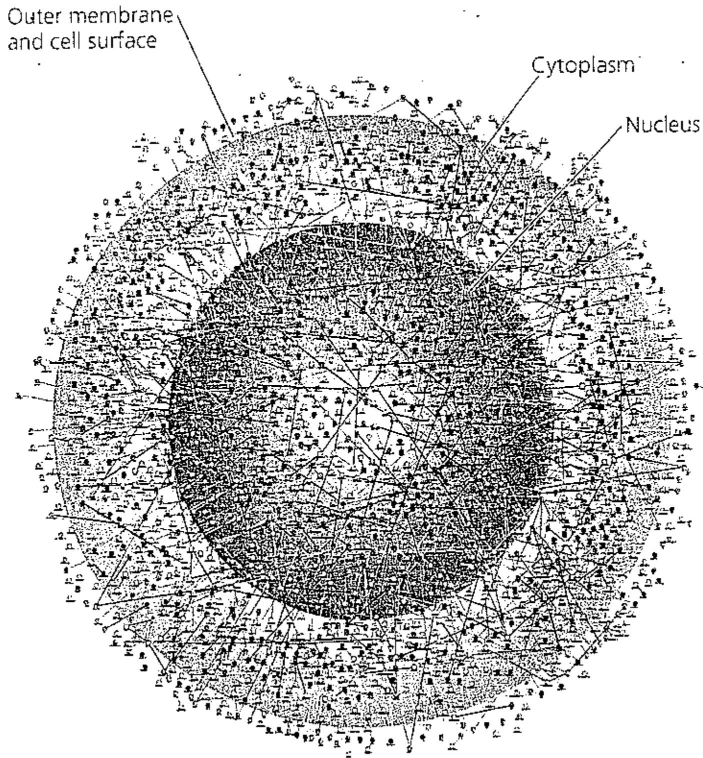
▶ **Figure 1.11 Modern biology as an information science.** Automatic DNA-sequencing machines and abundant computing power made the sequencing of the human genome possible. This facility in Walnut Creek, California, was one of many labs that collaborated in the international Human Genome Project.

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.

The best way to make sense of the deluge of data from genome-sequencing projects and the growing catalog of known protein functions is to apply a systems approach at the cellular and molecular levels. **Figure 1.12** illustrates the results of a large study that mapped a network of protein interactions within a cell of a fruit fly, a popular research organism. The model is based on a database of thousands of known proteins and their known interactions with other proteins. For example, protein A may attach to and alter the activities of proteins B, C, and D, which then go on to interact with still other proteins. The figure maps these protein partnerships to their cellular locales.

The basics of the systems strategy are straightforward. First, it is necessary to inventory as many parts of the system as possible, such as all the known genes and proteins in a cell (an application of reductionism). Then it is necessary to investigate how each part behaves in relation to others in the working system—all the protein-protein interactions, in the case of our fly cell example. Finally, with the help of computers and specialized software, it is possible to pool all the data into the kind of system network pictured in Figure 1.12.

Though the basic idea of systems biology is simple, the practice is not, as you would expect from the complexity of biological systems. It has taken three key research developments to bring systems biology within reach. 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



▲ **Figure 1.12 A systems map of interactions among proteins in a cell.** This diagram maps 2,346 proteins (dots) and their network of interactions (lines connecting the proteins) in a fruit fly cell. Systems biologists develop such models from huge databases of information about molecules and their interactions in the cell. A major goal of this systems approach is to use the models to predict how one change, such as an increase in the activity of a particular protein, can ripple through the cell's molecular circuitry to cause other changes. The total number of proteins in this type of cell is probably in the range of 4,000 to 7,000.

the human genome possible are examples of high-throughput devices (see Figure 1.11). The second is **bioinformatics**, which is 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

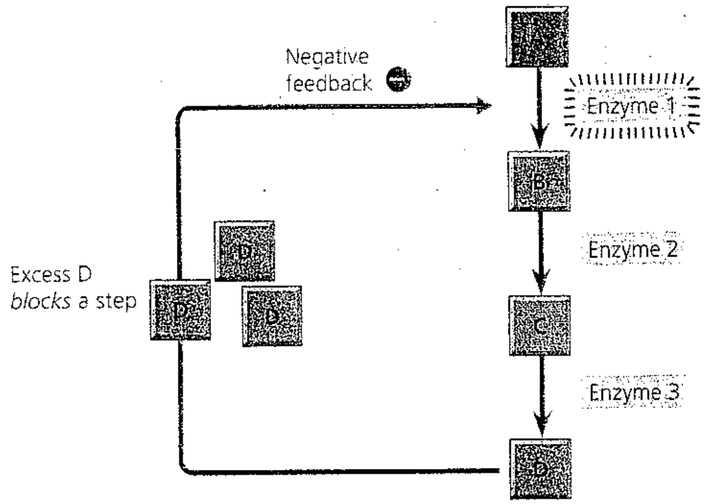
A kind of supply-and-demand economy applies to many biological systems. Consider your muscles, for instance. When your muscle cells require more energy during exercise, they increase their consumption of the sugar molecules that provide fuel. In contrast, when you rest, a different set of chemical reactions converts surplus sugar to storage molecules.

Like most of the cell's chemical processes, those that decompose or store sugar are accelerated, or catalyzed, by the specialized 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.

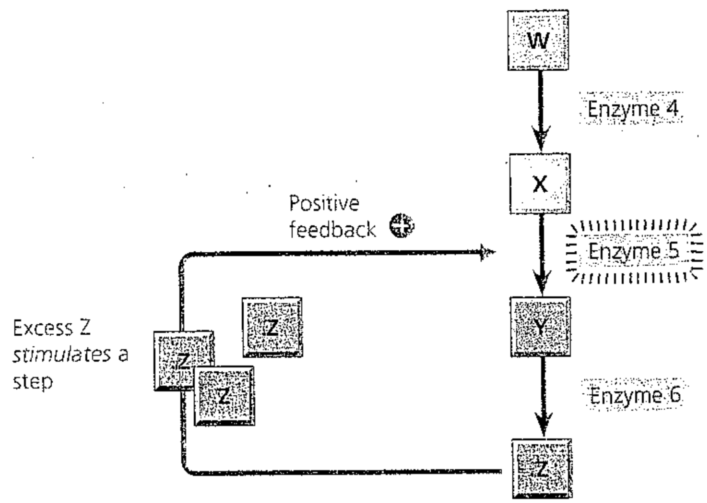
In feedback regulation, the output, or product, of a process regulates that very process. In life, the most common form of regulation is **negative feedback**, in which accumulation of an end product of a process slows that process. For example, the cell's breakdown of sugar generates chemical energy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



(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 if enzyme 2 were missing?

CONCEPT CHECK 1.1

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."
2. 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?
3. **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

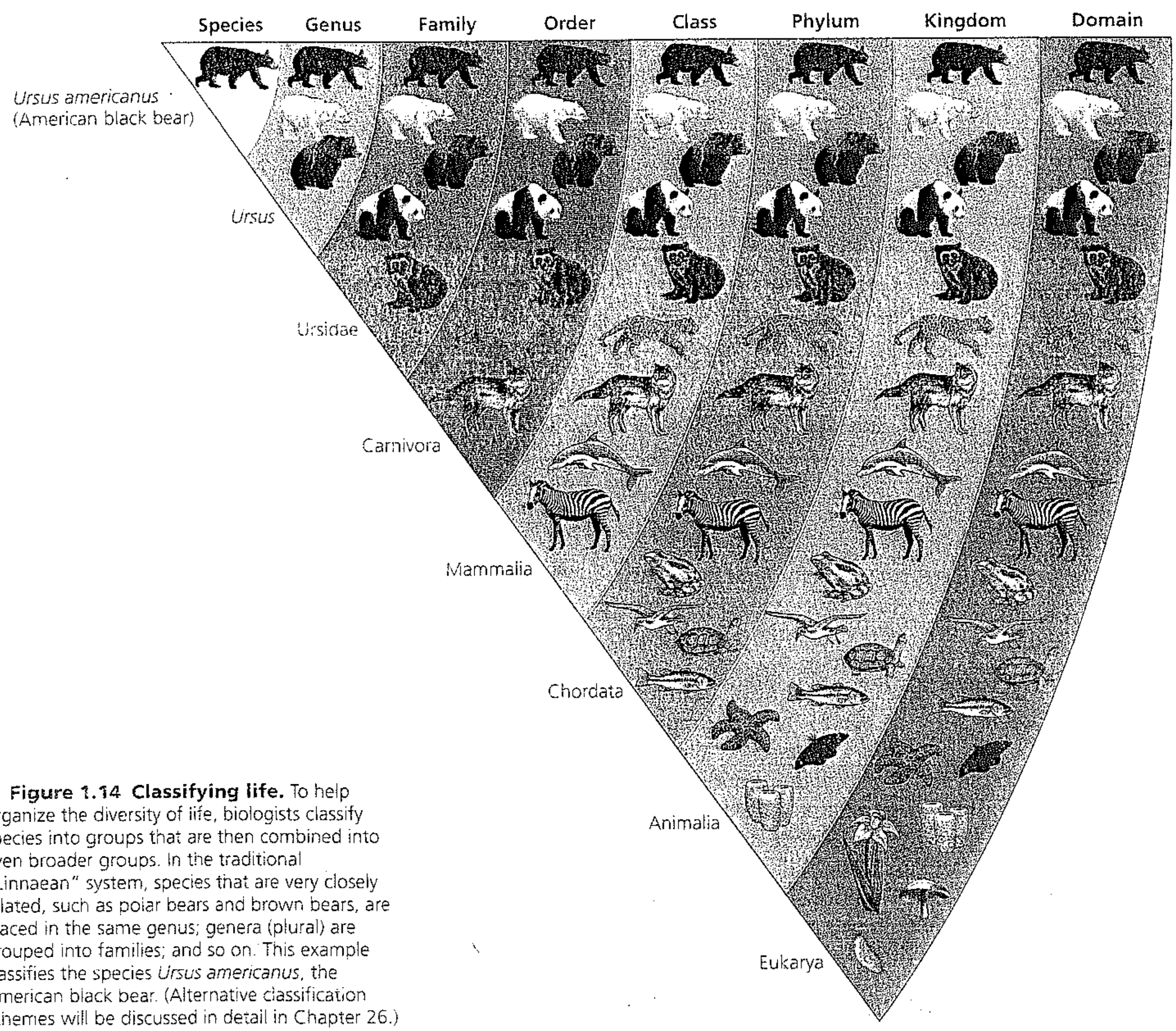
The Core Theme: Evolution accounts for the unity and diversity of life

The list of biological themes discussed under 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 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.

Organizing 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 6,300 species of prokaryotes (organisms with prokaryotic cells), 100,000 fungi, 290,000 plants, 52,000 vertebrates (animals with backbones), and 1 million insects (more than half of all known forms of life). 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 **(Figure 1.14)**.



▲ **Figure 1.14 Classifying life.** To help organize 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) 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.)

Grouping Species: The Basic Idea

There is a human tendency to group diverse items according to similarities. For instance, perhaps you organize your music collection by artist. And then maybe you group the various artists into broader categories, such as rock, jazz, and classical. In the same way, grouping species that are similar is natural for us. 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 (see Figure 1.14). You will learn more about this taxonomic scheme in Chapter 26. For now, we will focus on kingdoms and domains, the broadest units of classification.

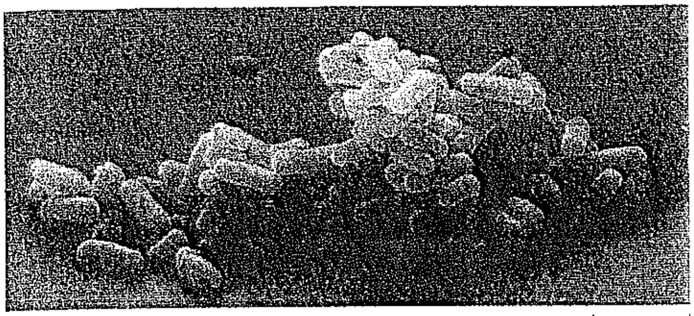
The Three Domains of Life

Until a few decades ago, most biologists adopted a taxonomic scheme that divided the diversity of life into five kingdoms: plants, animals, fungi, single-celled eukaryotic organisms, and prokaryotes. Since then, new methods, such as comparisons of DNA sequences from different species, have led to an ongoing reevaluation of the number and boundaries of kingdoms. Researchers have proposed anywhere from six kingdoms to dozens of kingdoms. But as debate continues at the kingdom level, there is a consensus that the kingdoms of life can now 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 **domain Bacteria** and **domain Archaea** are all prokaryotic. Most prokaryotes are single-celled and microscopic. In the five-kingdom system, bacteria

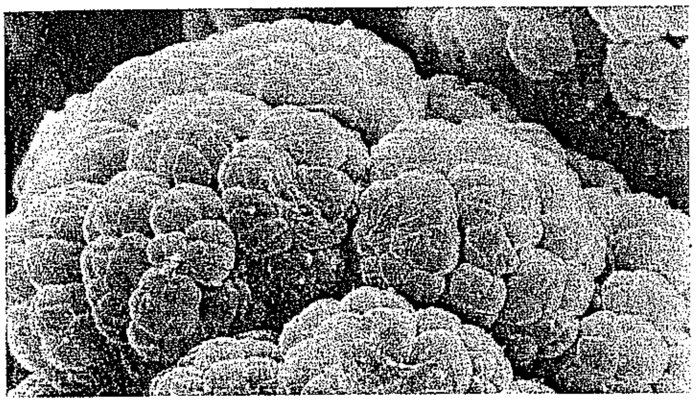
(a) DOMAIN BACTERIA

▼ **Bacteria** are the most diverse and widespread prokaryotes and are now divided among multiple kingdoms. Each of the rod-shaped structures in this photo is a bacterial cell.



(b) DOMAIN ARCHAEA

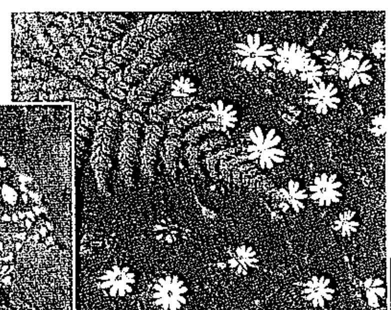
▼ Many of the prokaryotes known as **archaea** live in Earth's extreme environments, such as salty lakes and boiling hot springs. Domain Archaea includes multiple kingdoms. The photo shows a colony composed of many cells.



(c) DOMAIN EUKARYA

▲ **Protists** (multiple kingdoms) are unicellular eukaryotes and their relatively simple multicellular relatives. Pictured here is an assortment of protists inhabiting pond water. Scientists are currently debating how to assign the protists to kingdoms that accurately reflect their evolutionary relationships.

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



▲ **Kingdom Plantae** consists of multicellular eukaryotes that carry out photosynthesis, the conversion of light energy to the chemical energy in food.

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

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

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**. In the era of the five-kingdom scheme, most single-celled eukaryotes, such as the microorganisms known as protozoans, were placed in a single kingdom, "Protista." Many biologists extended the boundaries of kingdom Protista to include some multicellular forms, such as seaweeds, that are closely related to certain unicellular protists. The recent taxonomic trend has been to split the protists into several groups at the kingdom level. In addition to these protistan groups, domain Eukarya 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 foods 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.

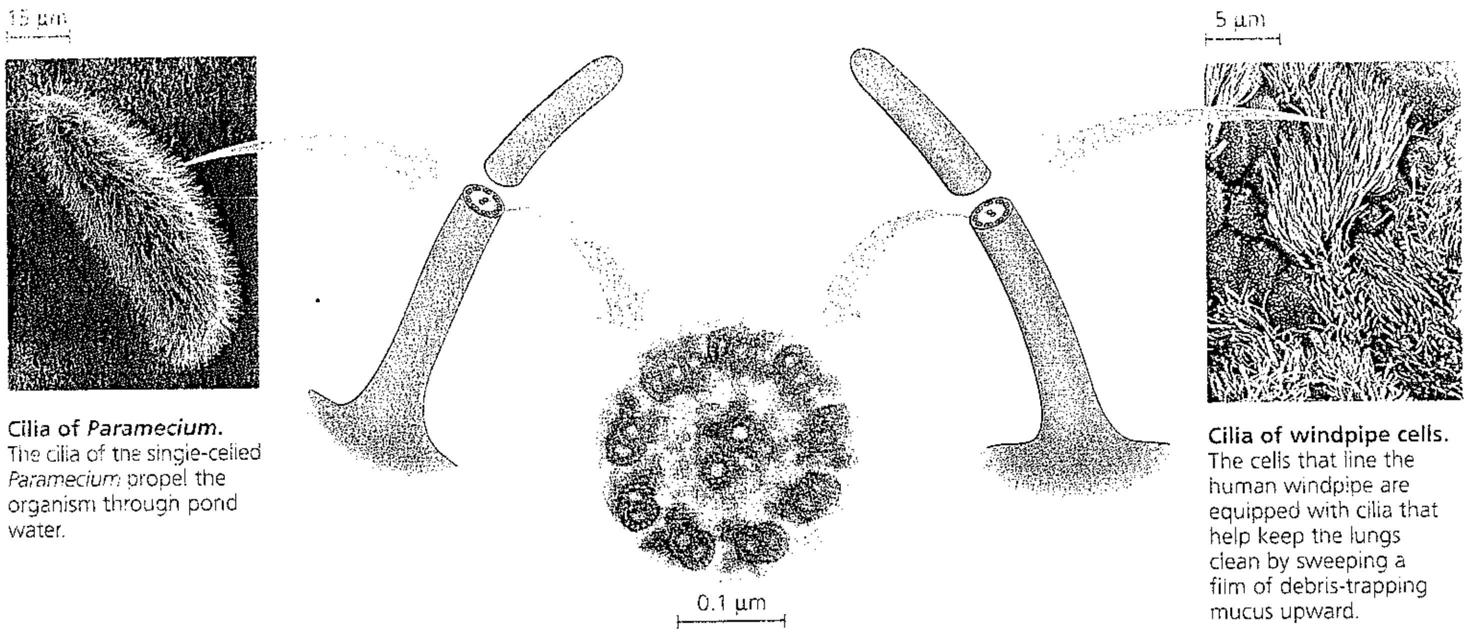
Unity in the Diversity of Life

As diverse as life is, it also displays remarkable unity. Earlier we mentioned the similar skeletons of different vertebrate animals, but similarities are even more striking at the molecular and cellular levels. For example, the universal genetic language of DNA is common to organisms as different as bacteria and animals. Unity is also evident 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 a 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" almost synonymous with the concept of evolution **(Figure 1.18)**.



Cilia of *Paramecium*. The cilia of the single-celled *Paramecium* propel the organism through pond water.

Cilia of windpipe cells. The cells that line the human windpipe are equipped with cilia that help keep the lungs clean by sweeping a film of debris-trapping mucus upward.

Cross section of a cilium, as viewed with an electron microscope

▲ **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 paramecia 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.

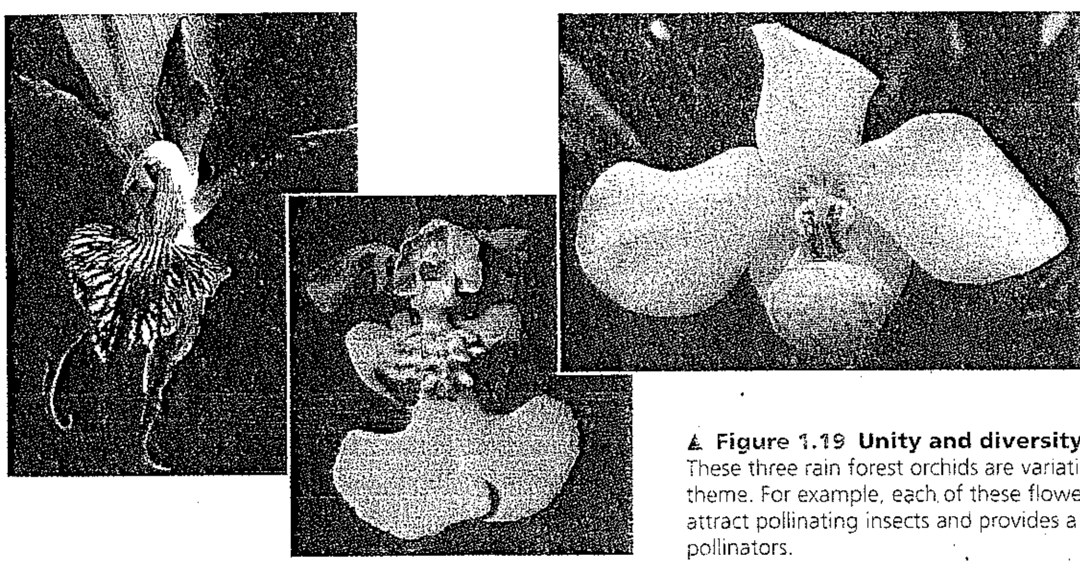
▲ **Figure 1.17 Digging into the past.** Paleontologist Paul Sereno, of the University of Chicago, gingerly excavates the leg bones of a dinosaur fossil in Niger.

The Origin of Species articulated two main points. First, Darwin presented evidence to support his view that contemporary species arose from a succession of ancestors. (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 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 to propose a mechanism for descent with modification. He called this evolutionary mechanism natural selection.

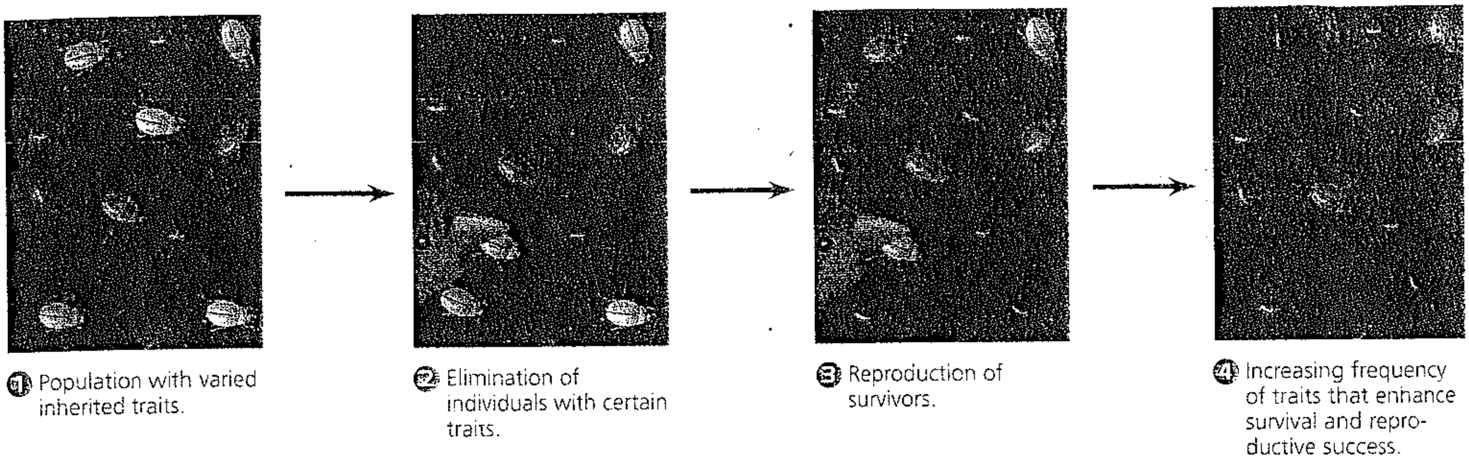
▲ **Figure 1.18 Charles Darwin as a young man.**

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 observations from nature: Individuals in a population vary in their traits, many of which seem to be heritable (passed on from parents to offspring). Also, a population can produce far more offspring than can survive to produce offspring of their own. With more individuals than the environment can support, competition is inevitable. Lastly, species generally suit their environments. For instance, birds living where tough seeds are a good food source may 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 fit individuals. Over many generations, a higher and higher proportion



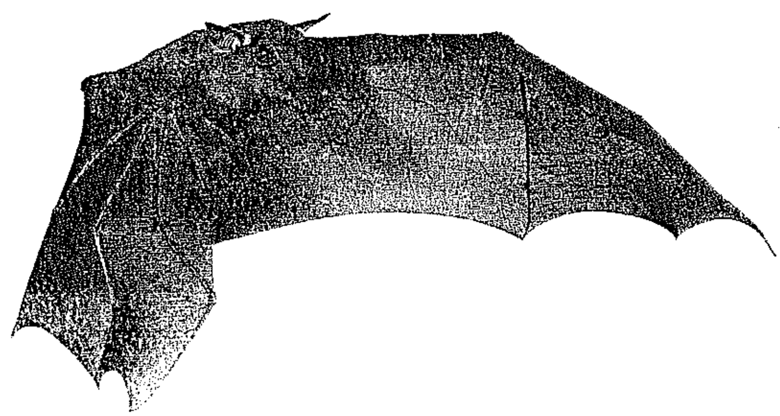
▲ **Figure 1.19 Unity and diversity in the orchid family.** These three rain forest orchids are variations on a common floral theme. For example, each of these flowers has a liplike petal that helps attract pollinating insects and provides a landing platform for the pollinators.



▲ **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.

of individuals in a population will have the advantageous traits. Evolution occurs as the unequal reproductive success of individuals adapts the population to its environment.

Darwin called this mechanism of evolutionary adaptation "natural selection" because the natural environment "selects" for the propagation of certain traits. The example 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 (**Figure 1.21**).



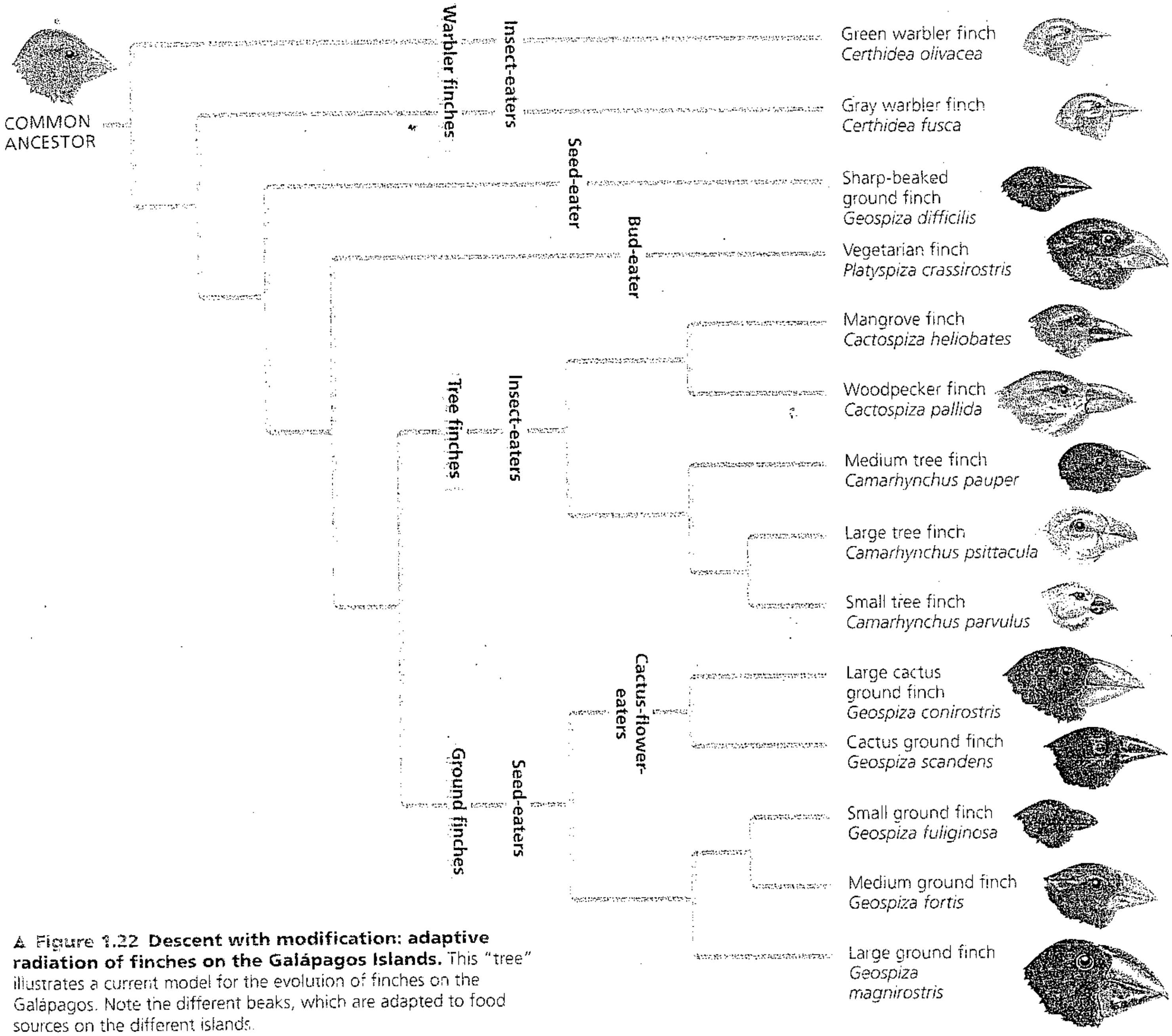
▲ **Figure 1.21 Evolutionary adaptation.** Bats, the only mammals capable of active flight, have wings with webbing between extended "fingers." In the Darwinian view of life, such adaptations are refined by natural selection.

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



▲ **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.

thought to have originated on the mainland of South America like many Galápagos organisms, the ancestral finches are now thought to have come from islands of the Carribean.) 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 of organism 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

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. On the eukaryotic branch, three of the subbranches are 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

Scientists use two main forms of inquiry in their study of nature

The word *science* is derived from a Latin verb meaning "to know." Science is a way of knowing about 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 genome 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.

Biologists use two main types of scientific inquiry: discovery science and hypothesis-based science. Discovery science is mostly about *describing* nature. Hypothesis-based science is mostly about *explaining* nature. Most scientific inquiries combine these two research approaches.

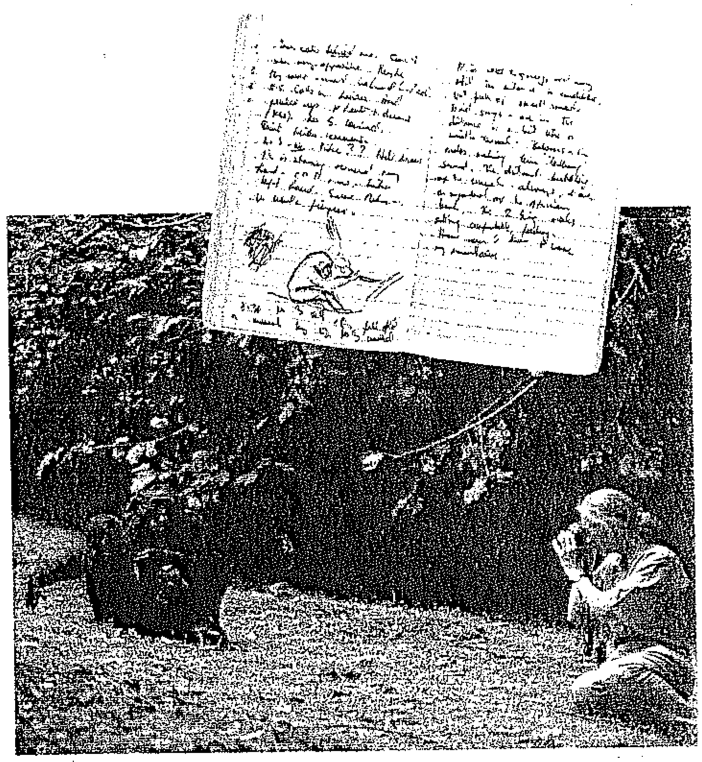
Discovery Science

Sometimes called descriptive science, **discovery science** describes natural structures and processes as accurately as possible through careful observation and analysis of data. For example, it is discovery science that has built our understanding of cell structure, and it is discovery science that is 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 jungle in Tanzania (**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 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.



▲ **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.

Induction in Discovery Science

Discovery science can lead to important conclusions based on a type of logic called induction, or **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 biologists discovering cells in the diverse biological specimens they observed with microscopes. The careful observations and data analyses of discovery science, along with the generalizations reached by induction, are fundamental to our understanding of nature.

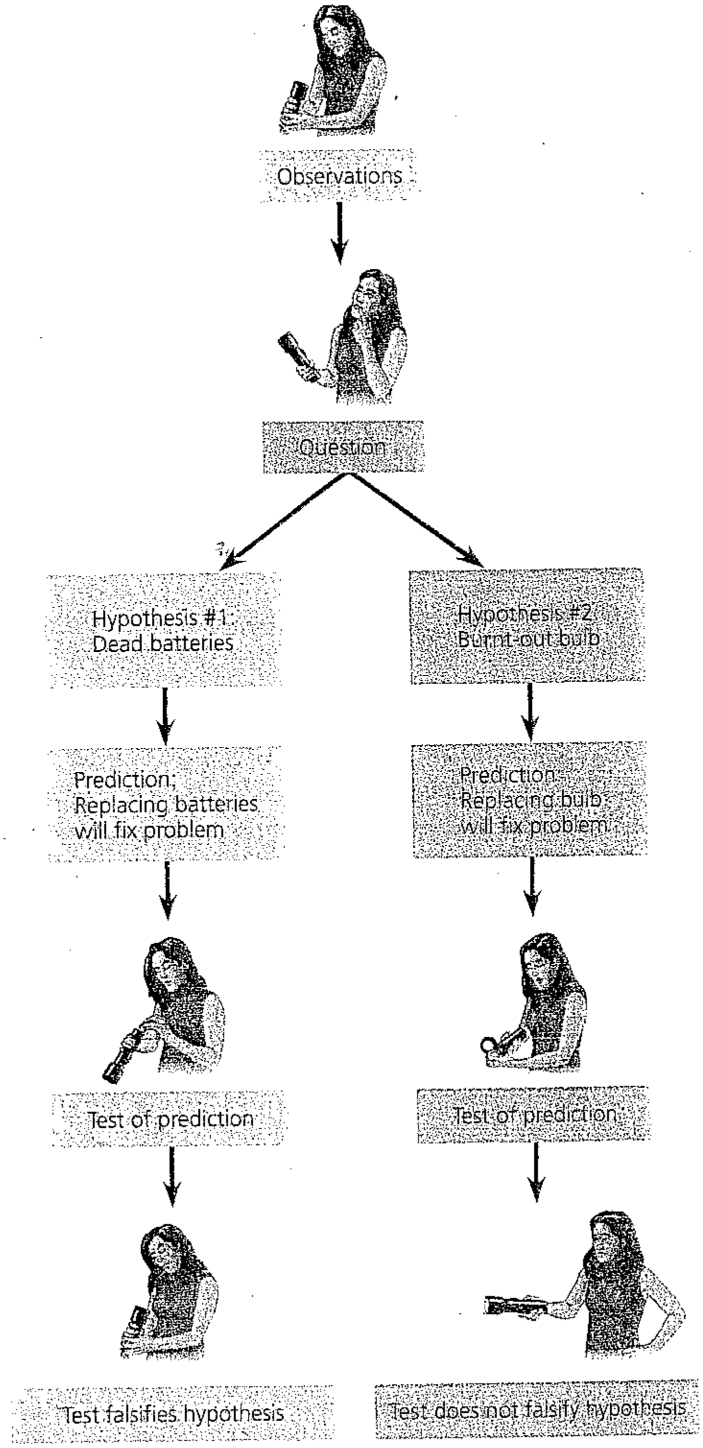
Hypothesis-Based Science

The observations and inductions of discovery science 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 an educated guess, based on experience and on the data available from discovery science. 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 hypothesis-based science clearly has its origins in the human tendency to figure things out by trial and error.



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

Deduction: The "If . . . Then" Logic of Hypothesis-Based Science

A type of logic called deduction is built into hypothesis-based science. Deduction contrasts with induction, which, remember, is reasoning from a set of specific observations to reach a general conclusion. In **deductive reasoning**, the logic 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).

In hypothesis-based science, 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.

A Closer Look at Hypotheses in Scientific Inquiry

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: Try to devise a test to falsify the hypothesis that invisible campground ghosts are fooling with your flashlight!

The flashlight inquiry illustrates another key point about hypothesis-based science. The ideal is to frame two or more alternative hypotheses and design experiments to falsify those candidate explanations. In addition to the two explanations tested in Figure 1.24, 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 malfunction?

We can mine the flashlight scenario for still one more important lesson about hypothesis-based science. Although the burnt-out bulb hypothesis stands up as the most likely explanation, notice that the testing supports that hypothesis *not* by proving that it is correct, but by not eliminating it through falsification. Perhaps the bulb was simply loose and the new bulb was inserted correctly. We could attempt to falsify the burnt-out bulb hypothesis by trying another experiment—removing the bulb and carefully reinstalling it. 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 attempts to falsify it while testing eliminates (falsifies) alternative hypotheses.

The Myth 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 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.

There is still another reason that good science need not conform exactly to any one method of inquiry: Discovery science has contributed much to our understanding of nature without most of the steps of the so-called scientific method.

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 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 discovery science and hypothesis-based science, you should be able to recognize these forms of inquiry in a case study of actual scientific research.

The story begins with a set of observations and generalizations from discovery science. 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 such "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 poisonous snake called the eastern coral snake has warning coloration: bold, alternating rings of red, yellow (or white), and black. Predators rarely attack these 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 nonpoisonous snake named the scarlet kingsnake mimics the ringed coloration of the coral snake.

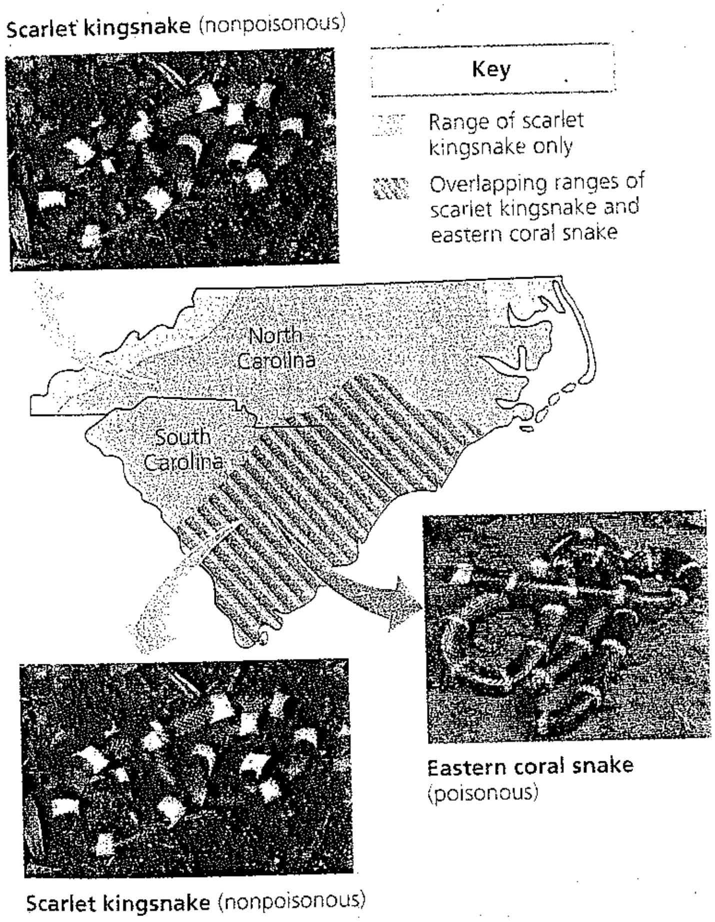
Both types of snakes live in the Carolinas, but the kingsnakes' geographic range also extends into regions where no coral snakes are found (see Figure 1.25). The geographic distribution of the snakes made it possible to test the key prediction of the mimicry hypothesis. Avoiding snakes with warning coloration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

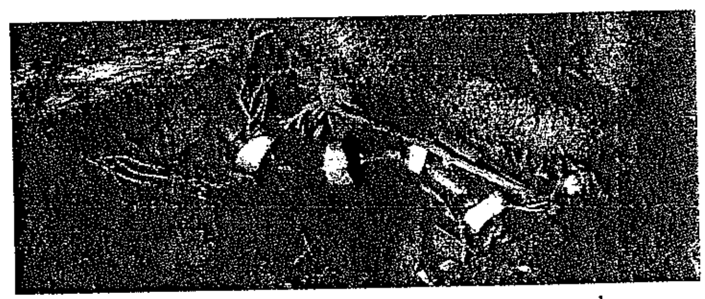
To test the prediction, Harcombe made hundreds of artificial snakes out of wire covered with plasticine. He fashioned two versions of fake snakes: an *experimental group* with the red, black, and white ring pattern of kingsnakes; and a *control group* of plain brown artificial snakes as a basis of comparison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

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

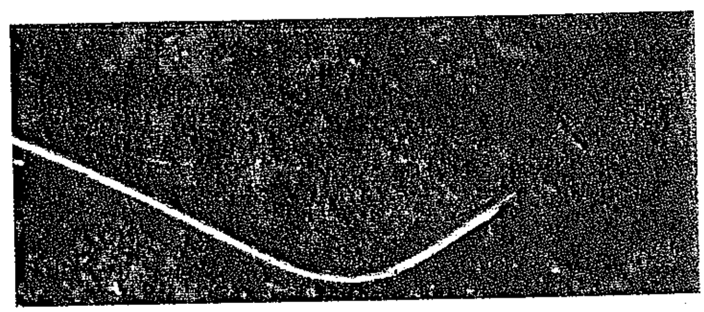
The data fit the key prediction of the mimicry hypothesis. Compared to the brown artificial snakes, the ringed artificial snakes were attacked by predators less frequently *only* in field sites within the geographic range of the poisonous coral



▲ **Figure 1.25 The geographic ranges of a poisonous snake and its mimic.** The scarlet kingsnake (*Lampropeltis triangulum*) mimics the warning coloration of the poisonous eastern coral snake (*Micrurus 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.** You can see where a bear chomped on the brown artificial snake in (b).

nakes. **Figure 1.27** summarizes the field experiments that he researchers carried out. This figure also introduces a fornat we will use throughout the book for other examples of biılogical inquiry.

Designing Controlled Experiments

The snake mimicry experiment is an example of a **controlled experiment**, one that is designed to compare an experimenal 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 experinent 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 *canceling* their effects by using control groups.

Limitations of Science

Scientific inquiry is a powerful way to learn about nature, but there are limitations to the kinds of questions it can answer. These limits are set by science's requirements that hypotheses be testable and falsifiable and that observations and experimental results be repeatable.

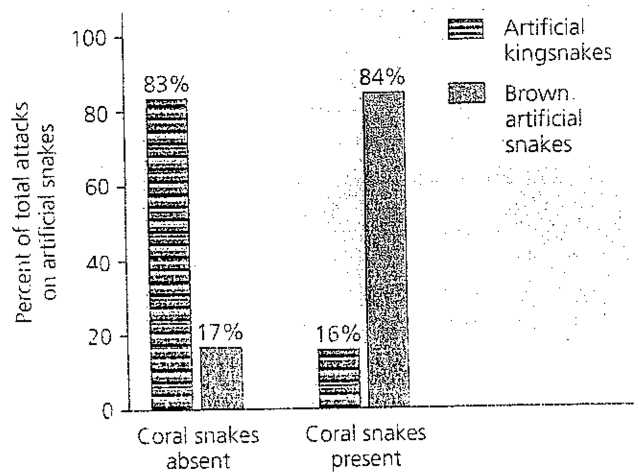
Observations that can't be verified may be interesting or even entertaining, but they cannot count as evidence in scientific inquiry. The headlines of supermarket tabloids would have you believe that humans are occasionally born with the head of a dog and that some of your classmates are extraterrestrials. 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 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.

▼ Figure 1.27 Inquiry

Does the presence of poisonous 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 poisonous 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 the two snakes cohabit and half in the area where coral snakes were 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 were present, most attacks were on brown artificial snakes. Where coral snakes were absent, most attacks were on artificial kingsnakes.



CONCLUSION The field experiments support the mimicry hypothesis by not falsifying the prediction that imitation of coral snakes is only effective 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 the ringed coloration failed to repel predators where coral snakes were absent. (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*.

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

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.

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 poisonous snakes is an adaptation that protects nonpoisonous 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. 468.)

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 five-kingdom theory of biological diversity 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.

Model Building in Science

You may work with many models in your biology course this year. Perhaps you'll model cell division by using pipe cleaners as chromosomes. Or maybe you'll practice using mathematical models to predict the growth of a bacterial population. Scientists often construct models as representations of natural phenomena. Scientific **models** can take many forms, including diagrams (such as the evolutionary tree in Figure 1.22), graphs, three-dimensional objects, computer programs, or mathematical equations.

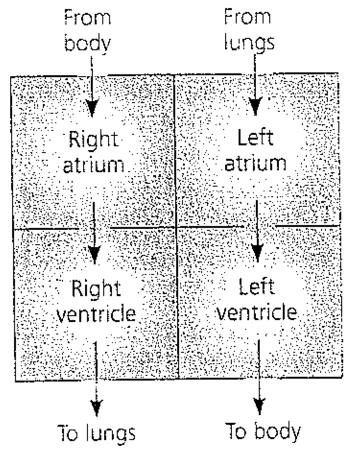


Figure 1.28 A model of the blood flow through the four chambers of a human heart.

The blood picks up oxygen (and releases carbon dioxide) in the lungs and releases oxygen (and picks up carbon dioxide) in the rest of the body. From the model shown here, predict what would happen if there were a small hole between the two ventricles.

Choosing the most appropriate type of model depends on what needs to be communicated and explained about the object, idea, or process the model is to represent. Some models need to be as lifelike as possible. Other models are more useful if they are simple schematics. For example, the simple diagram in **Figure 1.28** does a good job of modeling blood flow through the chambers of a human heart without looking anything like a real heart. A heart model designed to help train a physician to perform heart surgery would look very different. Whatever the design of a model, the test of its success is how well it fits the available data, how comfortably it accommodates new observations, how accurately it predicts the outcomes of new experiments or observations, and how effectively it communicates.

The Culture of Science

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 1.29**). 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.

Figure 1.29 Science as a social process. In her New York University laboratory, plant biologist Gloria Coruzzi mentors one of her students in the methods of molecular biology.

Both cooperation and competition characterize the scientific culture. Scientists working in the same research field often check one another's claims by attempting to confirm observations or repeat experiments. And when several scientists converge on the same research question, there is all the excitement of a race. Scientists enjoy the challenge of being first with an important discovery or key experiment.

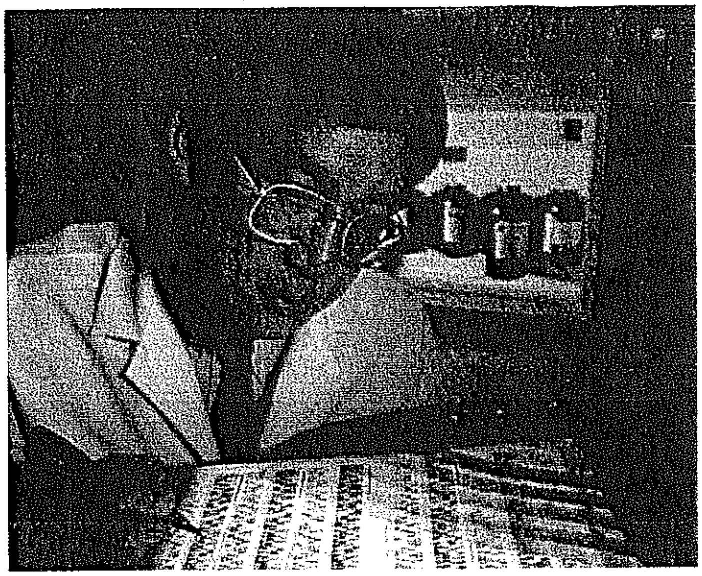
The biology community is part of society at large, embedded in the cultural milieu of the times. For example, changing attitudes about career choices have increased the proportion of women in biology, which has in turn affected the emphasis in certain research fields. A few decades ago, for instance, biologists who studied the mating behavior of animals focused mostly on competition among males for access to females. More recent research, however, emphasizes the important role that females play in choosing mates. For example, in many bird species, females prefer the bright coloration that "advertises" a male's vigorous health, a behavior that enhances the female's probability of having healthy offspring.

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.

Science, Technology, and Society

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 other scientists often speak of "discoveries," while engineers and other technologists more often speak of "inventions." And the beneficiaries of those inventions include scientists, who put new technology to work in their research; the impact of information technology on systems biology is just one example. Thus, science and technology are interdependent.

The potent combination of science and technology has dramatic effects on society. For example, discovery of the structure of DNA by Watson and Crick half a century ago and subsequent achievements in DNA science led to the technologies of DNA engineering that are transforming many applied fields, including medicine, agriculture, and forensics (**Figure 1.30**). Perhaps Watson and Crick envisioned that their discovery would someday produce important applications, but it is unlikely that they could have predicted exactly what all those applications would be.



▲ **Figure 1.30 DNA technology and crime scene investigation.** Forensic technicians can use traces of DNA extracted from a blood sample or other body tissue collected at a crime scene to produce molecular "fingerprints." The stained bands you see in this photograph represent fragments of DNA, and the pattern of bands varies from person to person.

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?

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.

CONCEPT CHECK 1.3

1. Contrast inductive reasoning with deductive reasoning.
2. Why is natural selection called a theory?
3. **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.

Chapter 1 Review

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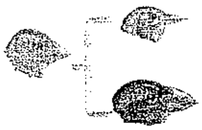
SUMMARY OF KEY CONCEPTS

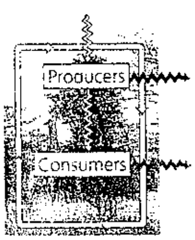
CONCEPT 1.1

Themes connect the concepts of biology (pp. 3–11)



▶ **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.

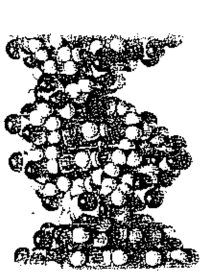
▶ ***Theme:* New properties emerge at each level in the biological hierarchy** The hierarchy of life unfolds as follows: biosphere > ecosystem > community > population > organism > organ system > organ > tissue > cell > organelle > molecule > atom. With each step "upward" from atoms, new properties emerge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



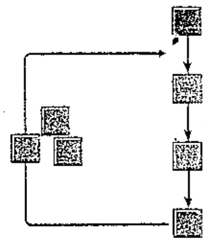
▶ ***Theme:* Organisms interact with their environments, exchanging matter and energy** An organism's environment includes other organisms as well as nonliving factors. Whereas chemical nutrients recycle within an ecosystem, energy flows through an ecosystem. All organisms must perform work, which requires energy. Energy flows from sunlight to producers 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:* Cells are an organism's basic units 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. RNA that is not translated into protein serves other important functions.



▶ ***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.

MEDIA

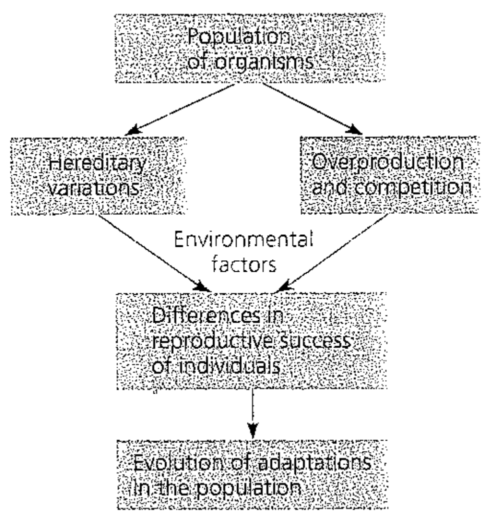
Activity The Levels of Life Card Game
Activity Energy Flow and Chemical Cycling
Activity Form Fits Function: Cells
Activity Comparing Prokaryotic and Eukaryotic Cells
Activity Heritable Information: DNA
Activity Regulation: Negative and Positive Feedback

CONCEPT 1.2

The Core Theme: Evolution accounts for the unity and diversity of life (pp. 12–18)

▶ **Organizing the Diversity of Life** 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.

▶ **Charles Darwin and the Theory of Natural Selection** Darwin proposed natural selection as the mechanism for evolutionary adaptation of populations to their environments.



▶ **The Tree of Life** 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.

MEDIA

Activity Classification Schemes
Investigation How Do Environmental Changes Affect a Population?
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CONCEPT 1.3

Scientists use two main forms of inquiry in their study of nature (pp. 18–24)

- **Discovery Science** In discovery science, scientists observe and describe some aspect of the world and use inductive reasoning to draw general conclusions.
- **Hypothesis-Based Science** Based on observations, scientists propose hypotheses that lead to predictions and then test the hypotheses by seeing if the predictions come true. Deductive reasoning is used in testing hypotheses: If a hypothesis is correct, and we test it, then we can expect a particular outcome. Hypotheses must be testable and falsifiable.
- **A Case Study in Scientific Inquiry: Investigating Mimicry in Snake Populations** Experiments must be designed to demonstrate the effect of one variable by testing control groups and experimental groups that differ in only that one variable.
- **Limitations of Science** Science cannot address the possibility of supernatural phenomena because hypotheses must be testable and falsifiable, and observations and experimental results must be repeatable.
- **Theories in Science** A scientific theory is broad in scope, generates new hypotheses, and is supported by a large body of evidence.
- **Model Building in Science** Models of ideas, structures, and processes help us understand scientific phenomena and make predictions.
- **The Culture of Science** Science is a social activity characterized by both cooperation and competition.
- **Science, Technology, and Society** Technology is a method or device that applies scientific knowledge for some specific purpose.

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Activity Science, Technology, and Society: DDT

TESTING YOUR KNOWLEDGE

SELF-QUIZ

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. understand the integration of all levels of biological organization from molecules to the biosphere.
   b. simplify complex problems by reducing the system into smaller, less complex units.
   c. construct models of 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. 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 zig-zag motion.
   d. The six pairs of robins hatched an average of three chicks.
   e. The contents of the stomach are mixed every 20 seconds.

8. Which of the following best describes the logic of hypothesis-based science?
   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.

9. A controlled experiment is one that
   a. proceeds slowly enough that a scientist can make careful records of the results.
   b. may include experimental groups and control groups tested in parallel.

c. is repeated many times to make sure the results are accurate.
d. keeps all environmental variables constant.
e. is supervised by an experienced scientist.

10. 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 in all cases; hypotheses are usually falsified by tests.

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.

For Self-Quiz answers, see Appendix A.

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EVOLUTION CONNECTION

12. 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?

SCIENTIFIC INQUIRY

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

SCIENCE, TECHNOLOGY, AND SOCIETY

14. The fruits of wild species of tomato are tiny compared to the giant beefsteak tomatoes available today. This difference in fruit size is almost entirely due to the larger number of cells in the domesticated fruits. Plant molecular biologists have recently discovered genes that are responsible for controlling cell division in tomatoes. Why would such a discovery be important to producers of other kinds of fruits and vegetables? To the study of human development and disease? To our basic understanding of biology?

The Chemistry of Life

AN INTERVIEW WITH

Deborah M. Gordon

What does an ant sense as it goes about its daily chores? Mainly chemicals—because these are the cues ants use to navigate their environment. The interactions of ants with each other and their surroundings are the research focus of Deborah M. Gordon, a professor of biological sciences at Stanford University. While at Stanford, Dr. Gordon has won several awards for excellence in teaching, as well as recognition for her research in the Arizona desert and the tropics of South America. And through appearances on radio, TV nature shows, and her book *Ants at Work: How an Insect Society Is Organized* (Free Press, 1999), Dr. Gordon has shared her fascination with ant society with people around the world.

How did you get interested in biology?
In my first year in college, thinking of a career in medicine as a possibility, I took introductory chemistry and biology. But those courses just gave me a lot of information that I couldn't really put together. I ended up majoring in French. But I was also very interested in math and in music theory, because I like looking at patterns and understanding how they change over time. Then, in my senior year, I took a course in comparative anatomy, which completely changed my view of biology. That course showed me that evolution is a process that changes patterns in interesting ways.

After graduation, curious about the human body and health, I came to Stanford to take the medical school course in human anatomy. I stayed to complete a master's degree in biology. Then, although I still wasn't sure what I wanted to do with my life, I entered a Ph.D. program at Duke. It was there that I began research on ant behavior—and I loved it.

Students of biology have to study chemistry as well. How is chemistry relevant to ant behavior?
Ants don't see very well; they operate mostly by chemical communication. If you work on ants, you have to think about chemistry because chemicals are critically important in the ant's world. For example, the ants I study in Arizona use long-lasting chemical cues to identify themselves and to mark their nest area. Ants also use many short-term chemical cues called pheromones, which they secrete in certain situations. The best known are alarm pheromones, which are what make ants run around in circles when they're disturbed. Some ants secrete a pheromone from the tip of the abdomen that marks where they walk and creates a trail that other ants can follow. Ants have 12 or 14 different glands that secrete different substances. We really don't know what they're all for, or how many chemical combinations an ant can respond to. In addition to chemicals used in communication, some ants produce antibiotics or chemical defenses against predators. Other ants use chemicals to kill certain plants [see Chapter 2, pp. 30–31].

Why do you study ants?
What interests me about ants is that ants live in societies without any central control. Yet individual ants are very limited in what they can do; each can take in only local information. No ant can figure out what needs to be done for the good of the colony. The big question for me is: How can an ant colony function when nobody's in charge and each ant can only perceive what's right around it?

What about the queens? Please tell us more about how ants live.
There are 10,000 to 12,000 species of ants. They all live in colonies, each with one or a few reproductive females, called queens. The queens lay eggs, using sperm stored from a mating that preceded her establishment of the colony. The rest of the colony—all the ants you see walking around—are her daughters, sterile female workers. These workers do all the work, and they do it without any direction from the queen. Males, born from unfertilized eggs, are produced only once a year, just in time to join virgin queens in a mating flight. Soon after mating, they die.

What exactly do worker ants do?
The ants I study in Arizona, called harvester ants, perform four kinds of tasks. Some workers forage for food. Some patrol; that is, they go out early in the morning and decide where the foragers should go that day. Others do nest-maintenance work, building chambers underground and then carrying out the excess sand. And still others work on the refuse pile, or midden, which they mark with the colony's specific odor. Different groups of ants perform each of the four tasks.

Tell us about your research in Arizona.
At my research site in Arizona, where I've been working for more than 20 years, I study a population of about 300 colonies of harvester ants. Each year my students and I map the locations of the colonies that make up this population. We identify all the colonies that were there the year before, figure out which ones have died, and map the new ones. In this way I can follow the same colonies year after year. I get to know them quite well. I have found that colonies last 15 to 20 years.

In addition to observing the ant colonies, we do simple experiments where we change the ants' environment in some way and observe how the ants respond. For example, in the last few years we've been studying how a colony regulates the number of ants that go out to forage. We've learned that each ant uses its recent history of interactions with other ants to decide what to do next. An ant uses odors to identify the task of the ants it meets. Each ant is coated with a layer of grease, made of chemicals called hydrocarbons. Each task group—the foragers, the patrollers, the nest maintenance workers, and the midden workers—has a unique mixture of hydrocarbons, which the ants secrete and spread on each other by grooming. We've found that, as an ant spends time outside, the proportions of different hydrocarbons on its body changes.

What causes this change?

The heat of the sun. We learned this from an experiment in which we took ants that had been working inside the nest and exposed them to different conditions. After exposure to high temperatures and low humidity for long enough times, these ants came to smell like foragers. So it's not that foragers secrete something different as they do their task but that doing the task changes them. Just as a carpenter gets calluses from holding tools, an ant comes to smell different from the work it does. The ants of a colony all secrete the same mixture of hydrocarbons, but each ant's chemical profile changes depending on what it does.

What tells an ant what to do? For example, what tells an ant to forage?

We've learned that ants use their recent experience of quick antennal contacts with each other to decide what to do. The antennae are their organs of chemical perception. Anyone who has watched ants has seen them meet and touch antennae, and when they do that, they smell each other, detecting the chemicals on each other's body. But a single interaction is not an instruction; a forager meeting another ant is not saying, "Go forage." It's the *pattern* of encounters that conveys the message.

How did you figure that out?

Working with Michael Greene, who's now at the University of Colorado at Denver, we've been able to extract the hydrocarbons from the ants' bodies and put them on little glass beads, and we've found that the ants respond to a bead coated with ant hydrocarbons as if it were an ant. So by dropping these coated beads into the nest, we can figure out how the ants react to encounters with an ant of a particular task group.

Recently we've been working on how foragers use the rate at which other foragers come in with food to decide whether to go out again. This rate gives feedback about how much food is out there. A forager looking for food won't come back until it finds something; if it has to stay out for 45 minutes, it will. But when there's an abundance of food near the nest, the foragers return quickly. The returning ants provide positive feedback: The faster ants come back, the more ants go out.

We've found that harvester ants respond surprisingly quickly to changes in the frequency of encounters with other ants. This rapid response is probably driven by the ants' short memories—only about 10 seconds.

So the answer to the question of what controls a colony is the aggregate of "decisions" made in the simple interactions between individual ants. Are there analogies in other areas of biology?

A system without central control, built from simple, interacting components, is called a "complex system," and scientists in many areas of biology are interested in such systems. One obvious analog to an ant colony is a brain. Your brain is composed of neurons (nerve cells), but no single neuron knows how to think about, for example, the subject of ants—although your brain as a whole can think about ants. The brain operates without central control, in the sense that there isn't a master neuron in there that says, "OK, you guys, you do ants." Yet somehow all of the simple interactions among the neurons add up to the brain's very complex functioning. Another analogy is the growth of an embryo: The cells of an embryo all have the same DNA, but as the embryo grows, its cells take on different forms and functions. Nobody says, "OK, you become liver, you become bone." Instead, as a result of molecular interactions among cells, the embryo develops tissues of different types.

In your book, the colony is spoken of as if it were an organism. Does evolution operate on the level of the colony?

Yes, because the whole colony cooperates to make more queens and males that go out and start new colonies. A colony's behavior can determine how many offspring colonies it makes. In the long term, I'd like to understand how natural selection is acting on ant behavior (if it is). Why does it matter to the colony that it behaves in a certain way?

Now for a practical question: How can we deal with ant invasions in our homes?

It depends on where you live. In Northern California, the invading ants are usually Argentine ants, whose activity is clearly connected to the weather. The ants come into everybody's houses at the same time—when it rains or is very hot and dry—and they go out at the same time. The most important thing to remember is that putting out pesticide, especially when you don't have ants, sends pesticide into the groundwater but doesn't have much effect on the numbers of ants. I don't like having ants in my kitchen—I always take it personally—but I know that when I do, everybody else does, too. And covering or washing away a trail works only briefly—about 20 minutes for Argentine ants, as I found out in an experiment. Blocking off the places where ants are coming in is the best approach.

Ant-bait devices, from which foraging ants are supposed to carry poison to their nest, can work for ants that have one queen in a central nest. Such ants include carpenter ants, which enter houses in many parts of the United States. These ants nest in decaying wood, though contrary to their reputation, they don't eat wood. Ant baits don't work at all for the Argentine ants because these ants have many queens and many nests and you are unlikely to reach all the queens with the poison.

What advice do you have for undergraduates interested in a research career?

Students should try to experience several kinds of research, involving different kinds of activities. The best way to find out if you like doing research—whether it's working in the field or in the lab—is to try it.

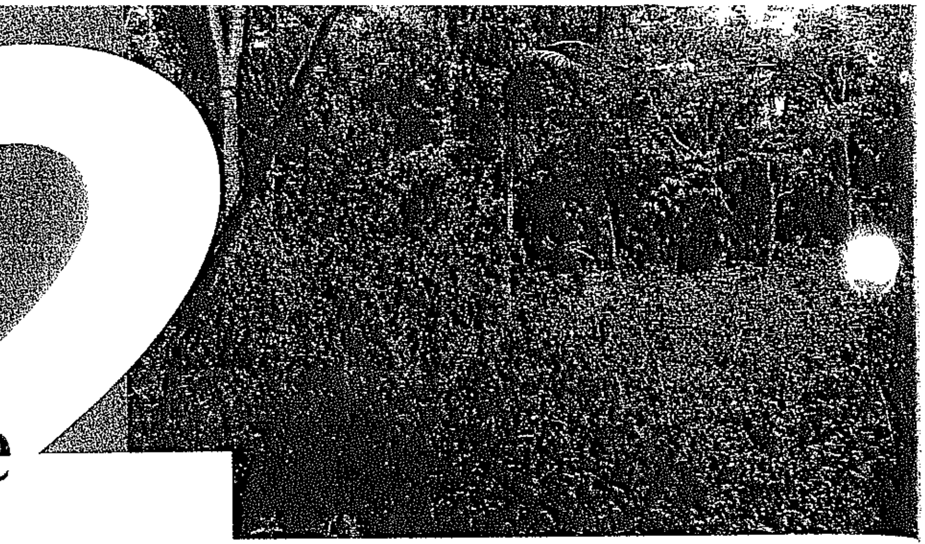
How can an ant colony function when nobody's in charge and each ant can only perceive what's right around it?

Left to right: Deborah Gordon; Megan Frederickson, Lisa Urry, and Jane Reece

Inquiry in Action

Learn about an experiment by Deborah Gordon and her graduate student Megan Frederickson in Inquiry Figure 2.2 on page 31. Read and analyze the original paper in *Inquiry in Action: Interpreting Scientific Papers*.

2 The Chemical Context of Life



▲ **Figure 2.1 Who tends this garden?**

KEY CONCEPTS

2.1 **Matter consists of chemical elements in pure form and in combinations called compounds**

2.2 **An element's properties depend on the structure of its atoms**

2.3 **The formation and function of molecules depend on chemical bonding between atoms**

2.4 **Chemical reactions make and break chemical bonds**

OVERVIEW

A Chemical Connection to Biology

The Amazon rain forest in South America is a showcase for the diversity of life on Earth. Colorful birds, insects, and other animals live among a myriad of trees, shrubs, vines, and wildflowers, and an excursion along a waterway or a forest path typically reveals a lush variety of plant life. Visitors traveling near the Amazon's headwaters in Peru are therefore surprised to come across tracts of forest like that seen in the foreground of the photo in **Figure 2.1**. This patch is almost completely dominated by a single plant species—a willowy flowering tree called *Duroia hirsuta*. Travelers may wonder if the garden is planted and maintained by local people, but the indigenous people are as mystified as the visitors. They call these stands of *Duroia* trees "devil's gardens," from a legend attributing them to an evil forest spirit.

Seeking a scientific explanation, a research team working under Deborah Gordon, who is interviewed on pages 28–29, recently solved the "devil's garden" mystery. **Figure 2.2** describes their main experiment. The researchers showed that the "farmers" who create and maintain these gardens are actually ants that live in the hollow stems of the *Duroia* trees. The ants do not plant the *Duroia* trees, but they prevent other plant species from growing in the garden by injecting intruders with a poisonous chemical. In this way, the ants create space for the growth of the *Duroia* trees that serve as their home. With the ability to maintain and expand its habitat, a single colony of devil's garden ants can live for hundreds of years.

The chemical the ants use to weed their garden turns out to be formic acid. This substance is produced by many species of ants and in fact got its name from the Latin word for ant, *formica*. In many cases, the formic acid probably serves as a disinfectant that protects the ants against microbial parasites. The devil's garden ant is the first ant species found to use formic acid as a herbicide. This use of a chemical is an important addition to the list of functions mediated by chemicals in the insect world. Scientists already know that chemicals play an important role in insect communication, attraction of mates, and defense against predators.

Research on devil's gardens is only one example of the relevance of chemistry to the study of life. Unlike a list of college courses, nature is not neatly packaged into the individual natural sciences—biology, chemistry, physics, and so forth. Biologists specialize in the study of life, but organisms and their environments are natural systems to which the concepts of chemistry and physics apply. Biology is a multidisciplinary science.

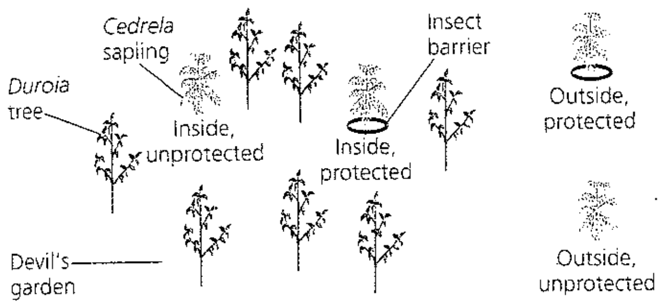
This unit of chapters introduces basic concepts of chemistry that will apply throughout our study of life. We will make many connections to the themes introduced in Chapter 1. One of these themes is the organization of life into a hierarchy of structural levels, with additional properties emerging at each successive level. In this unit, we will see how emergent properties are apparent at the lowest levels of biological organization—such as the ordering of atoms into molecules and the interactions of those molecules within cells. Somewhere in the transition from molecules to cells, we will cross the blurry boundary between nonlife and life. This chapter focuses on the chemical components that make up all matter.

▼ Figure 2.2 Inquiry

What creates "devil's gardens" in the rain forest?

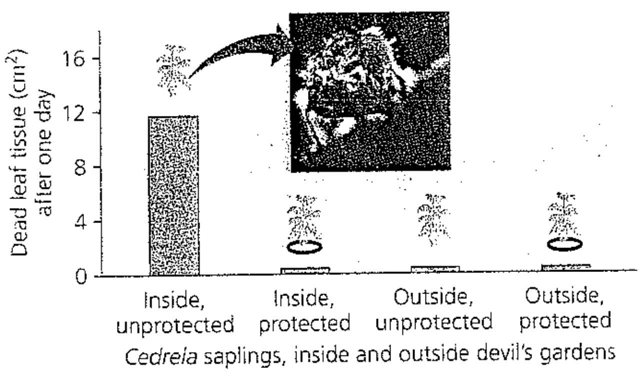
EXPERIMENT Working under Deborah Gordon and with Michael Greene, graduate student Megan Frederickson sought the cause of "devil's gardens," stands of a single species of tree, *Duroia hirsuta*. One hypothesis was that ants living in these trees, *Myrmelachista schumanni*, produce a poisonous chemical that kills trees of other species; another was that the *Duroia* trees themselves kill competing trees, perhaps by means of a chemical.

To test these hypotheses, Frederickson did field experiments in Peru. Two saplings of a local nonhost tree species, *Cedrela odorata*, were planted inside each of ten devil's gardens. At the base of one, a sticky insect barrier was applied; the other was unprotected. Two more *Cedrela* saplings, with and without barriers, were planted about 50 meters outside each garden.



The researchers observed ant activity on the *Cedrela* leaves and measured areas of dead leaf tissue after one day. They also chemically analyzed contents of the ants' poison glands.

RESULTS The ants made injections from the tips of their abdomens into leaves of unprotected saplings in their gardens (see photo). Within one day, these leaves developed dead areas (see graph). The protected saplings were uninjured, as were the saplings planted outside the gardens. Formic acid was the only chemical detected in the poison glands of the ants.



CONCLUSION Ants of the species *Myrmelachista schumanni* kill nonhost trees by injecting the leaves with formic acid, thus creating hospitable habitats (devil's gardens) for the ant colony.

SOURCE M. E. Frederickson, M. J. Greene, and D. M. Gordon, "Devil's gardens" bedevilled by ants, *Nature* 437:495–496 (2005).

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

WHAT IF? What would be the results if the unprotected saplings' inability to grow in the devil's gardens was caused by a chemical released by the *Duroia* trees rather than by the ants?

CONCEPT 2.1

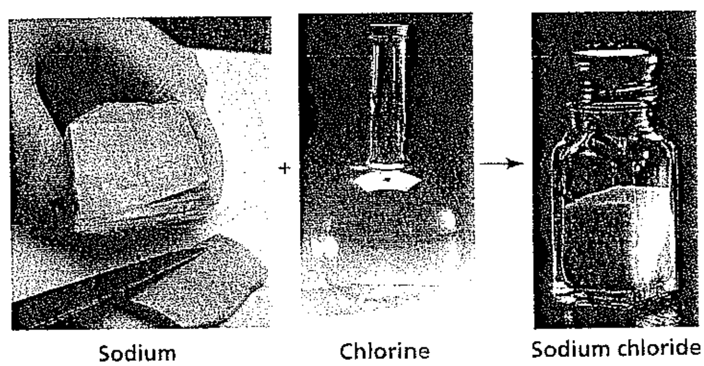
Matter consists of chemical elements in pure form and in combinations called compounds

Organisms are composed of **matter**, which is anything that takes up space and has mass.* Matter exists in many diverse forms. Rocks, metals, oils, gases, and humans are just a few examples of what seems an endless assortment of matter.

Elements and Compounds

Matter is made up of elements. An **element** is a substance that cannot be broken down to other substances by chemical reactions. Today, chemists recognize 92 elements occurring in nature; gold, copper, carbon, and oxygen are examples. Each element has a symbol, usually the first letter or two of its name. Some symbols are derived from Latin or German; for instance, the symbol for sodium is Na, from the Latin word *natrium*.

A **compound** is a substance consisting of two or more different elements combined in a fixed ratio. Table salt, for example, is sodium chloride (NaCl), a compound composed of the elements sodium (Na) and chlorine (Cl) in a 1:1 ratio. Pure sodium is a metal, and pure chlorine is a poisonous gas. When chemically combined, however, sodium and chlorine form an edible compound. Water (H_2O), another compound, consists of the elements hydrogen (H) and oxygen (O) in a 2:1 ratio. These are simple examples of organized matter having emergent properties: A compound has characteristics different from those of its elements **(Figure 2.3)**.



▲ **Figure 2.3 The emergent properties of a compound.** The metal sodium combines with the poisonous gas chlorine, forming the edible compound sodium chloride, or table salt.

* Sometimes we substitute the term *weight* for mass, although the two are not identical. Mass is the amount of matter in an object, whereas the weight of an object is how strongly that mass is pulled by gravity. The weight of an astronaut walking on the moon is approximately ⅙ that of the astronaut's weight on Earth, but his or her mass is the same. However, as long as we are earth-bound, the weight of an object is a measure of its mass; in everyday language, therefore, we tend to use the terms interchangeably.

Essential Elements of Life

About 25 of the 92 natural elements are known to be essential to life. Just four of these—carbon (C), oxygen (O), hydrogen (H), and nitrogen (N)—make up 96% of living matter. Phosphorus (P), sulfur (S), calcium (Ca), potassium (K), and a few other elements account for most of the remaining 4% of an organism's weight. **Table 2.1** lists by percentage the elements that make up the human body; the percentages for other organisms are similar. **Figure 2.4a** illustrates the effect of a deficiency of nitrogen, an essential element, in a plant.

Trace elements are those required by an organism in only minute quantities. Some trace elements, such as iron (Fe), are needed by all forms of life; others are required only by certain species. For example, in vertebrates (animals with backbones), the element iodine (I) is an essential ingredient of a hormone produced by the thyroid gland. A daily intake of only 0.15 milligram (mg) of iodine is adequate for normal activity of the human thyroid. An iodine deficiency in the diet causes the thyroid gland to grow to abnormal size, a condition called goiter (**Figure 2.4b**). Where it is available, iodized salt has reduced the incidence of goiter.

Table 2.1 Naturally Occurring Elements in the Human Body

Symbol	Element	Atomic Number (see p. 33)	Percentage of Human Body Weight
Elements making up about 96% of human body weight			
O	Oxygen	8	65.0
C	Carbon	6	18.5
H	Hydrogen	1	9.5
N	Nitrogen	7	3.3
Elements making up about 4% of human body weight			
Ca	Calcium	20	1.5
P	Phosphorus	15	1.0
K	Potassium	19	0.4
S	Sulfur	16	0.3
Na	Sodium	11	0.2
Cl	Chlorine	17	0.2
Mg	Magnesium	12	0.1

Elements making up less than 0.01% of human body weight (trace elements)

Boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), zinc (Zn)

(a) Nitrogen deficiency **(b) Iodine deficiency**

▲ **Figure 2.4 The effects of essential-element deficiencies.** **(a)** This photo shows the effect of nitrogen deficiency in corn (maize). In this controlled experiment, the taller plants on the left are growing in nitrogen-rich soil, and the shorter plants on the right in nitrogen-poor soil. **(b)** Goiter is an enlargement of the thyroid gland, resulting from a deficiency of the trace element iodine. The goiter of this Malaysian woman can probably be reversed by iodine supplements.

CONCEPT CHECK 2.1

1. Explain how table salt has emergent properties.
2. Is a trace element an essential element? Explain.
3. **WHAT IF?** Iron (Fe) is a trace element required for the proper functioning of hemoglobin, the molecule that carries oxygen in red blood cells. What might be the effects of an iron deficiency?

For suggested answers, see Appendix A.

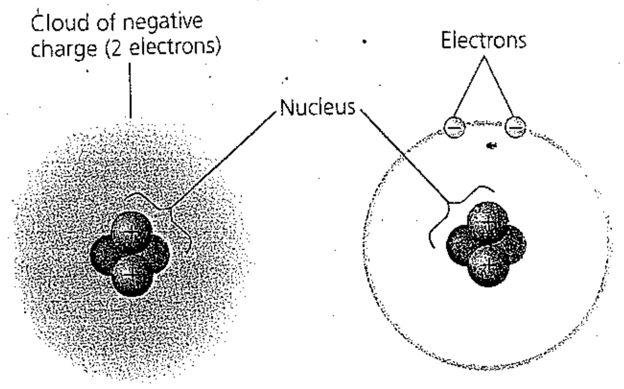
CONCEPT 2.2

An element's properties depend on the structure of its atoms

Each element consists of a certain kind of atom that is different from the atoms of any other element. An **atom** is the smallest unit of matter that still retains the properties of an element. Atoms are so small that it would take about a million of them to stretch across the period printed at the end of this sentence. We symbolize atoms with the same abbreviation used for the element that is made up of those atoms. For example, the symbol C stands for both the element carbon and a single carbon atom.

Subatomic Particles

Although the atom is the smallest unit having the properties of its element, these tiny bits of matter are composed of even smaller parts, called *subatomic particles*. Physicists have split the atom into more than a hundred types of particles, but only



(a) This model represents the electrons as a cloud of negative charge.

(b) In this even more simplified model, the electrons are shown as two small yellow spheres on a circle around the nucleus.

▲ **Figure 2.5 Simplified models of a helium (He) atom.** The helium nucleus consists of 2 neutrons (brown) and 2 protons (pink). Two electrons (yellow) exist outside the nucleus. These models are not to scale; they greatly overestimate the size of the nucleus in relation to the electron cloud.

three kinds of particles are relevant here: **neutrons, protons,** and **electrons.** Protons and electrons are electrically charged. Each proton has one unit of positive charge, and each electron has one unit of negative charge. A neutron, as its name implies, is electrically neutral.

Protons and neutrons are packed together tightly in a dense core, or **atomic nucleus,** at the center of an atom; protons give the nucleus a positive charge. The electrons form a sort of cloud of negative charge around the nucleus, and it is the attraction between opposite charges that keeps the electrons in the vicinity of the nucleus. **Figure 2.5** shows two models of the structure of the helium atom as an example.

The neutron and proton are almost identical in mass, each about 1.7×10^{-24} gram (g). Grams and other conventional units are not very useful for describing the mass of objects so minuscule. Thus, for atoms and subatomic particles (and for molecules, too), we use a unit of measurement called the **dalton,** in honor of John Dalton, the British scientist who helped develop atomic theory around 1800. (The dalton is the same as the *atomic mass unit,* or *amu,* a unit you may have encountered elsewhere.) Neutrons and protons have masses close to 1 dalton. Because the mass of an electron is only about 1/2,000 that of a neutron or proton, we can ignore electrons when computing the total mass of an atom.

Atomic Number and Atomic Mass

Atoms of the various elements differ in their number of subatomic particles. All atoms of a particular element have the same number of protons in their nuclei. This number of protons, which is unique to that element, is called the **atomic number** and is written as a subscript to the left of the symbol for the element. The abbreviation $_2He$, for example, tells us that an atom of the element helium has 2 protons in its nucleus. Unless otherwise indicated, an atom is neutral in electrical charge, which means that its protons must be balanced by an equal number of electrons. Therefore, the atomic number tells us the number of protons and also the number of electrons in an electrically neutral atom.

We can deduce the number of neutrons from a second quantity, the **mass number,** which is the sum of protons plus neutrons in the nucleus of an atom. The mass number is written as a superscript to the left of an element's symbol. For example, we can use this shorthand to write an atom of helium as ^4_2He. Because the atomic number indicates how many protons there are, we can determine the number of neutrons by subtracting the atomic number from the mass number: The helium atom, ^4_2He, has 2 neutrons. An atom of sodium, $^{23}_{11}Na$, has 11 protons, 11 electrons, and 12 neutrons. The simplest atom is hydrogen, ^1_1H, which has no neutrons; it consists of a single proton with a single electron.

As mentioned earlier, the contribution of electrons to mass is negligible. Therefore, almost all of an atom's mass is concentrated in its nucleus. Because neutrons and protons each have a mass very close to 1 dalton, the mass number is an approximation of the total mass of an atom, called its **atomic mass.** So we might say that the atomic mass of sodium ($^{23}_{11}Na$) is 23 daltons, although more precisely it is 22.9898 daltons.

Isotopes

All atoms of a given element have the same number of protons, but some atoms have more neutrons than other atoms of the same element and therefore have greater mass. These different atomic forms are called **isotopes** of the element. In nature, an element occurs as a mixture of its isotopes. For example, consider the three isotopes of the element carbon, which has the atomic number 6. The most common isotope is carbon-12, $^{12}_6C$, which accounts for about 99% of the carbon in nature. The isotope $^{12}_6C$ has 6 neutrons. Most of the remaining 1% of carbon consists of atoms of the isotope $^{13}_6C$, with 7 neutrons. A third, even rarer isotope, $^{14}_6C$, has 8 neutrons. Notice that all three isotopes of carbon have 6 protons; otherwise, they would not be carbon. Although the isotopes of an element have slightly different masses, they behave identically in chemical reactions. (The number usually given as the atomic mass of an element, such as 22.9898 daltons for sodium, is actually an average of the atomic masses of all the element's naturally occurring isotopes.)

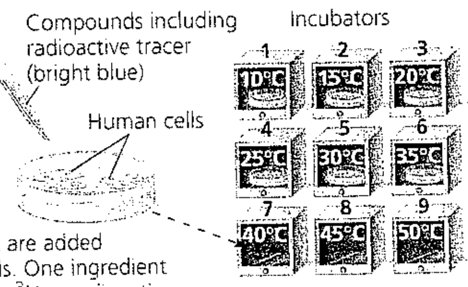
Both ^{12}C and ^{13}C are stable isotopes, meaning that their nuclei do not have a tendency to lose particles. The isotope ^{14}C, however, is unstable, or radioactive. A **radioactive isotope** is one in which the nucleus decays spontaneously, giving off particles and energy. When the decay leads to a change in the

▼ Figure 2.6 Research Method

Radioactive Tracers

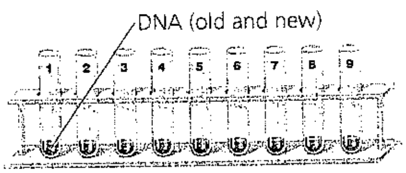
APPLICATION Scientists use radioactive isotopes to label certain chemical compounds, creating tracers that can be used to follow a metabolic process or locate the compound within an organism. In this example, radioactive tracers are being used to determine the effect of temperature on the rate at which cells make copies of their DNA.

TECHNIQUE



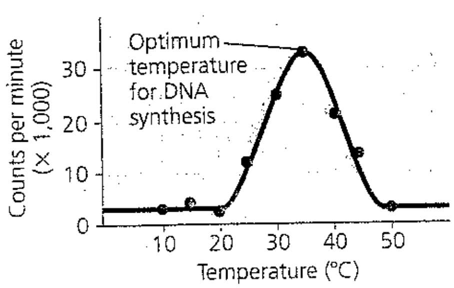
① Compounds used by cells to make DNA are added to human cells. One ingredient is labeled with ^3H, a radioactive isotope of hydrogen. Nine dishes of cells are incubated at different temperatures. The cells make new DNA, incorporating the radioactive tracer with ^3H.

② The cells are placed in test tubes; their DNA is isolated; and unused labeled compounds are removed.



③ A solution called scintillation fluid is added to the test tubes and they are placed in a scintillation counter. As the ^3H in the newly made DNA decays, it emits radiation that excites chemicals in the scintillation fluid, causing them to give off light. Flashes of light are recorded by the scintillation counter.

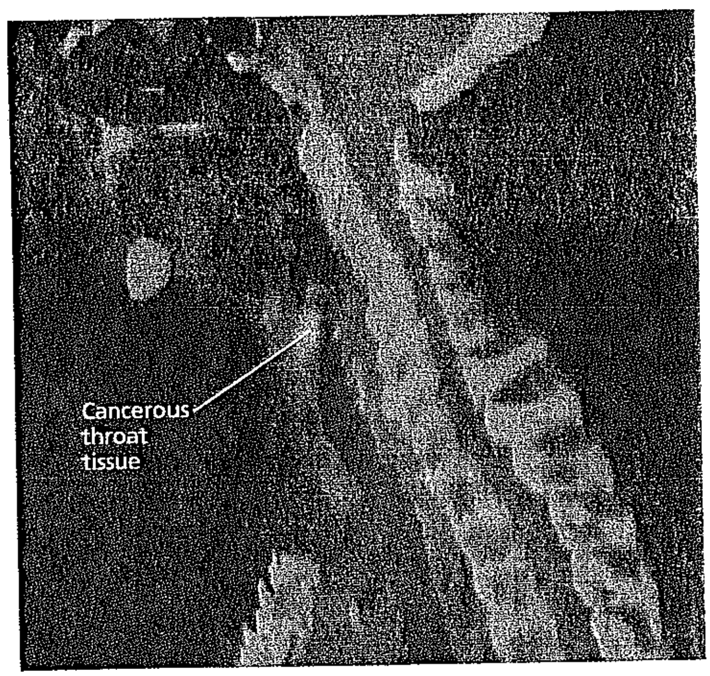
RESULTS The frequency of flashes, which is recorded as counts per minute, is proportional to the amount of the radioactive tracer present, indicating the amount of new DNA. In this experiment, when the counts per minute are plotted against temperature, it is clear that temperature affects the rate of DNA synthesis; the most DNA was made at 35°C.



number of protons, it transforms the atom to an atom of a different element. For example, radioactive carbon decays to form nitrogen.

Radioactive isotopes have many useful applications in biology. In Chapter 25, you will learn how researchers use measurements of radioactivity in fossils to date these relics of past life. Radioactive isotopes are also useful as tracers to follow atoms through metabolism, the chemical processes of an organism. Cells use the radioactive atoms as they would use nonradioactive isotopes of the same element, but the radioactive tracers can be readily detected. **Figure 2.6** presents an example of how biologists use radioactive tracers to monitor biological processes, in this case the synthesis of DNA by human cells.

Radioactive tracers are important diagnostic tools in medicine. For example, certain kidney disorders can be diagnosed by injecting small doses of substances containing radioactive isotopes into the blood and then measuring the amount of tracer excreted in the urine. Radioactive tracers are also used in combination with sophisticated imaging instruments, such as PET scanners, which can monitor chemical processes, such as those involved in cancerous growth, as they actually occur in the body **(Figure 2.7)**.



▲ **Figure 2.7 A PET scan, a medical use for radioactive isotopes.** PET, an acronym for positron-emission tomography, detects locations of intense chemical activity in the body. The patient is first injected with a nutrient such as glucose labeled with a radioactive isotope that emits subatomic particles. These particles collide with electrons made available by chemical reactions in the body. A PET scanner detects the energy released in these collisions and maps "hot spots," the regions of an organ that are most chemically active at the time. The color of the image varies with the amount of the isotope present, with the bright yellow color here identifying a region of cancerous throat tissue.

Although radioactive isotopes are very useful in biological research and medicine, radiation from decaying isotopes also poses a hazard to life by damaging cellular molecules. The severity of this damage depends on the type and amount of radiation an organism absorbs. One of the most serious environmental threats is radioactive fallout from nuclear accidents. The doses of most isotopes used in medical diagnosis, however, are relatively safe.

The Energy Levels of Electrons

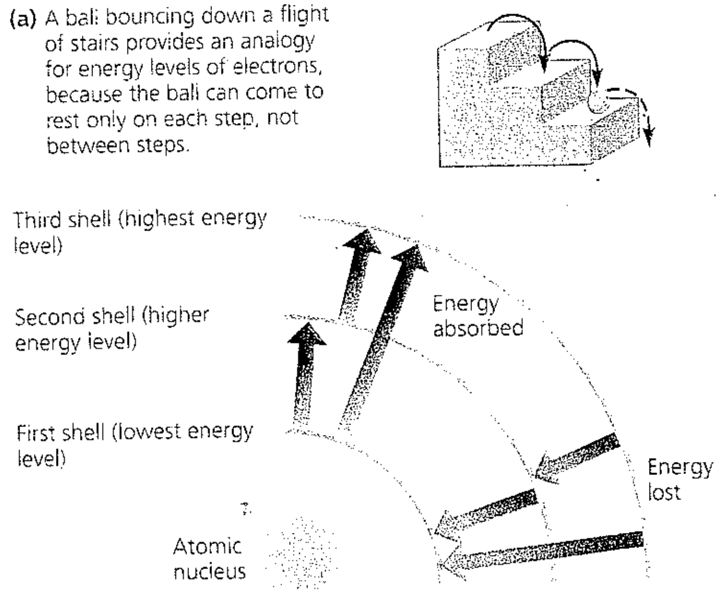
The simplified models of the atom in Figure 2.5 greatly exaggerate the size of the nucleus relative to the volume of the whole atom. If an atom of helium were the size of Yankee Stadium, the nucleus would be only the size of a pencil eraser in the center of the field. Moreover, the electrons would be like two tiny gnats buzzing around the stadium. Atoms are mostly empty space.

When two atoms approach each other during a chemical reaction, their nuclei do not come close enough to interact. Of the three kinds of subatomic particles we have discussed, only electrons are directly involved in the chemical reactions between atoms.

An atom's electrons vary in the amount of energy they possess. **Energy** is defined as the capacity to cause change—for instance, by doing work. **Potential energy** is the energy that matter possesses because of its location or structure. For example, water in a reservoir on a hill has potential energy because of its altitude. When the gates of the reservoir's dam are opened and the water runs downhill, the energy can be used to do work, such as turning generators. Because energy has been expended, the water has less energy at the bottom of the hill than it did in the reservoir. Matter has a natural tendency to move to the lowest possible state of potential energy; in this example, the water runs downhill. To restore the potential energy of a reservoir, work must be done to elevate the water against gravity.

The electrons of an atom have potential energy because of how they are arranged in relation to the nucleus. The negatively charged electrons are attracted to the positively charged nucleus. It takes work to move a given electron farther away from the nucleus, so the more distant an electron is from the nucleus, the greater its potential energy. Unlike the continuous flow of water downhill, changes in the potential energy of electrons can occur only in steps of fixed amounts. An electron having a certain amount of energy is something like a ball on a staircase (**Figure 2.8a**). The ball can have different amounts of potential energy, depending on which step it is on, but it cannot spend much time between the steps. Similarly, an electron's potential energy is determined by its energy level. An electron cannot exist in between energy levels.

An electron's energy level is correlated with its average distance from the nucleus. Electrons are found in different



(a) A ball bouncing down a flight of stairs provides an analogy for energy levels of electrons, because the ball can come to rest only on each step, not between steps.

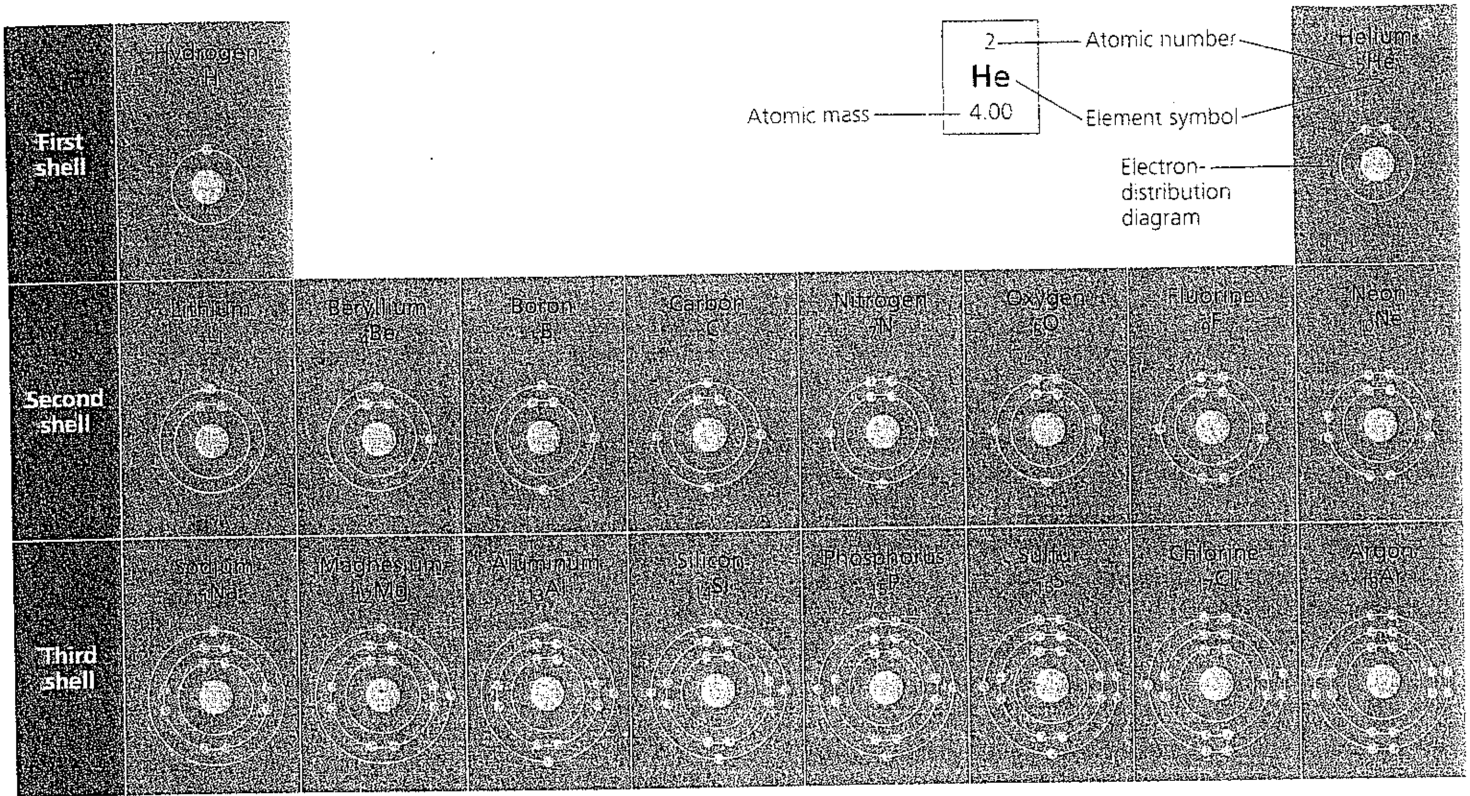
(b) An electron can move from one shell to another only if the energy it gains or loses is exactly equal to the difference in energy between the energy levels of the two shells. Arrows indicate some of the stepwise changes in potential energy that are possible.

▲ **Figure 2.8 Energy levels of an atom's electrons.** Electrons exist only at fixed levels of potential energy called electron shells.

electron shells, each with a characteristic average distance and energy level. In diagrams, shells can be represented by concentric circles (**Figure 2.8b**). The first shell is closest to the nucleus, and electrons in this shell have the lowest potential energy. Electrons in the second shell have more energy, and electrons in the third shell even more energy. An electron can change the shell it occupies, but only by absorbing or losing an amount of energy equal to the difference in potential energy between its position in the old shell and that in the new shell. When an electron absorbs energy, it moves to a shell farther out from the nucleus. For example, light energy can excite an electron to a higher energy level. (Indeed, this is the first step taken when plants harness the energy of sunlight for photosynthesis, the process that produces food from carbon dioxide and water.) When an electron loses energy, it "falls back" to a shell closer to the nucleus, and the lost energy is usually released to the environment as heat. For example, sunlight excites electrons in the surface of a car to higher energy levels. When the electrons fall back to their original levels, the car's surface heats up. This thermal energy can be transferred to the air or to your hand if you touch the car.

Electron Distribution and Chemical Properties

The chemical behavior of an atom is determined by the distribution of electrons in the atom's electron shells. Beginning with hydrogen, the simplest atom, we can imagine building the atoms of the other elements by adding 1 proton and 1 electron



▲ **Figure 2.9 Electron-distribution diagrams for the first 18 elements in the periodic table.** In a standard periodic table (see Appendix B), information for each element is presented as shown for helium in the inset. In the diagrams in this table, electrons are represented as yellow dots and electron shells as concentric circles. These diagrams are a convenient way to picture the distribution of an atom's electrons among its electron shells, but these simplified models do not accurately represent the shape of the atom or the location of its electrons. The elements are arranged in rows, each representing the filling of an electron shell. As electrons are added, they occupy the lowest available shell.

What is the atomic number of magnesium? How many protons and electrons does it have? How many electron shells? How many valence electrons?

at a time (along with an appropriate number of neutrons). **Figure 2.9**, an abbreviated version of what is called the *periodic table of the elements*, shows this distribution of electrons for the first 18 elements, from hydrogen ($_1H$) to argon ($_{18}Ar$). The elements are arranged in three rows, or periods, corresponding to the number of electron shells in their atoms. The left-to-right sequence of elements in each row corresponds to the sequential addition of electrons and protons. (See Appendix B for the complete periodic table.)

Hydrogen's 1 electron and helium's 2 electrons are located in the first shell. Electrons, like all matter, tend to exist in the lowest available state of potential energy. In an atom, this state is in the first shell. However, the first shell can hold no more than 2 electrons; thus, hydrogen and helium are the only elements in the first row of the table. An atom with more than 2 electrons must use higher shells because the first shell is full. The next element, lithium, has 3 electrons. Two of these electrons fill the first shell, while the third electron occupies the second shell. The second shell holds a maximum of 8 electrons. Neon, at the end of the second row, has 8 electrons in the second shell, giving it a total of 10 electrons.

The chemical behavior of an atom depends mostly on the number of electrons in its *outermost* shell. We call those outer electrons **valence electrons** and the outermost electron shell the **valence shell**. In the case of lithium, there is only 1 valence electron, and the second shell is the valence shell. Atoms with the same number of electrons in their valence shells exhibit similar chemical behavior. For example, fluorine (F) and chlorine (Cl) both have 7 valence electrons, and both form compounds when combined with the element sodium (see Figure 2.3). An atom with a completed valence shell is unreactive; that is, it will not interact readily with other atoms. At the far right of the periodic table are helium, neon, and argon, the only three elements shown in Figure 2.9 that have full valence shells. These elements are said to be *inert*, meaning chemically unreactive. All the other atoms in Figure 2.9 are chemically reactive because they have incomplete valence shells.

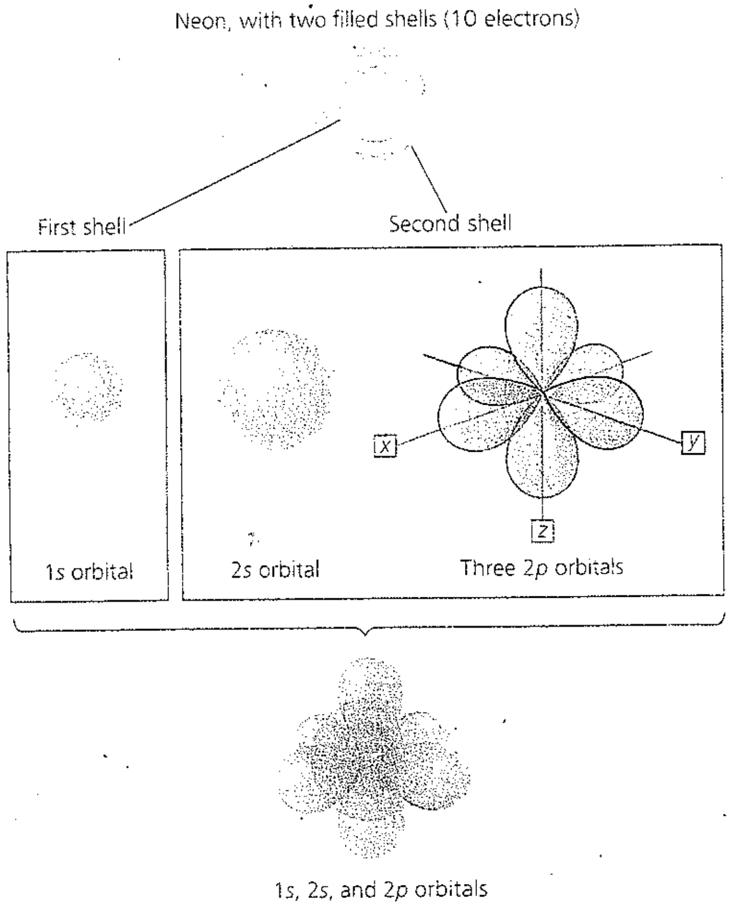
Electron Orbitals

In the early 1900s, the electron shells of an atom were visualized as concentric paths of electrons orbiting the nucleus, somewhat like planets orbiting the sun. It is still convenient to use two-dimensional concentric-circle diagrams to symbolize electron shells, as in Figure 2.9. However, you need to remember that each concentric circle represents only the

(a) Electron-distribution diagram. An electron-distribution diagram is shown here for a neon atom, which has a total of 10 electrons. Each concentric circle represents an electron shell, which can be subdivided into electron orbitals.

(b) Separate electron orbitals. The three-dimensional shapes represent electron orbitals—the volumes of space where the electrons of an atom are most likely to be found. Each orbital holds a maximum of 2 electrons. The first electron shell, on the left, has one spherical (*s*) orbital, designated 1*s*. The second shell, on the right, has one larger *s* orbital (designated 2*s* for the second shell) plus three dumbbell-shaped orbitals called *p* orbitals (2*p* for the second shell). The three 2*p* orbitals lie at right angles to one another along imaginary *x*-, *y*-, and *z*-axes of the atom. Each 2*p* orbital is outlined here in a different color.

(c) Superimposed electron orbitals. To show the complete picture of the electron orbitals of neon, we superimpose the 1*s* orbital of the first shell and the 2*s* and three 2*p* orbitals of the second shell.



▲ Figure 2.10 **Electron orbitals.**

average distance between an electron in that shell and the nucleus. Accordingly, the concentric-circle diagrams do not give a real picture of an atom. In reality, we can never know the exact location of an electron. What we can do instead is describe the space in which an electron spends most of its time. The three-dimensional space where an electron is found 90% of the time is called an **orbital**.

Each electron shell contains electrons at a particular energy level, distributed among a specific number of orbitals of distinctive shapes and orientations. **Figure 2.10** shows the orbitals of neon as an example. You can think of an orbital as a component of an electron shell. The first electron shell has only one spherical *s* orbital (called 1*s*), but the second shell has four orbitals: one large spherical *s* orbital (called 2*s*) and three dumbbell-shaped *p* orbitals (called 2*p* orbitals). (The third shell and other higher electron shells also have *s* and *p* orbitals, as well as orbitals of more complex shapes.)

No more than 2 electrons can occupy a single orbital. The first electron shell can therefore accommodate up to 2 electrons in its *s* orbital. The lone electron of a hydrogen atom occupies the 1*s* orbital, as do the 2 electrons of a helium atom. The four orbitals of the second electron shell can hold up to 8 electrons. Electrons in each of the four orbitals have nearly the same energy, but they move in different volumes of space.

The reactivity of atoms arises from the presence of unpaired electrons in one or more orbitals of their valence shells. As you will see in the next section, atoms interact in a way that completes their valence shells. When they do so, it is the *unpaired* electrons that are involved.

CONCEPT CHECK 2.2

1. A lithium atom has 3 protons and 4 neutrons. What is its atomic mass in daltons?
2. A nitrogen atom has 7 protons, and the most common isotope of nitrogen has 7 neutrons. A radioactive isotope of nitrogen has 8 neutrons. Write the atomic number and mass number of this radioactive nitrogen as a chemical symbol with a subscript and superscript.
3. How many electrons does fluorine have? How many electron shells? Name the orbitals that are occupied. How many electrons are needed to fill the valence shell?
4. **WHAT IF?** In Figure 2.9, if two or more elements are in the same row, what do they have in common? If two or more elements are in the same column, what do they have in common?

For suggested answers, see Appendix A.

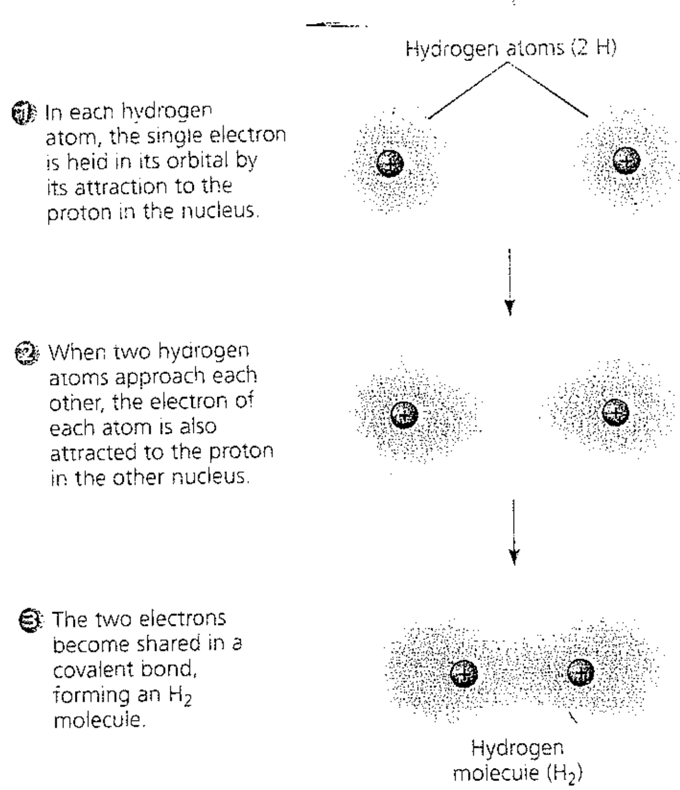
CONCEPT 2.3

The formation and function of molecules depend on chemical bonding between atoms

Now that we have looked at the structure of atoms, we can move up the hierarchy of organization and see how atoms combine to form molecules and ionic compounds. Atoms with incomplete valence shells can interact with certain other atoms in such a way that each partner completes its valence shell: The atoms either share or transfer valence electrons. These interactions usually result in atoms staying close together, held by attractions called **chemical bonds**. The strongest kinds of chemical bonds are covalent bonds and ionic bonds.

Covalent Bonds

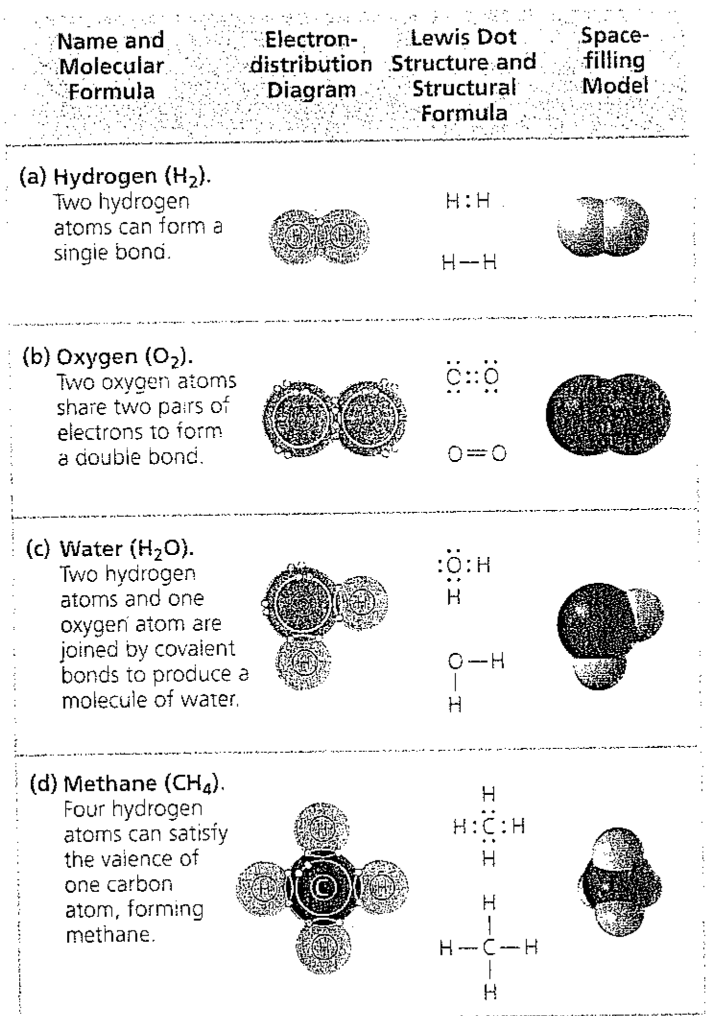
A **covalent bond** is the sharing of a pair of valence electrons by two atoms. For example, let's consider what happens when two hydrogen atoms approach each other. Recall that hydrogen has 1 valence electron in the first shell, but the shell's capacity is 2 electrons. When the two hydrogen atoms come close enough for their 1*s* orbitals to overlap, they can share their electrons **(Figure 2.11)**. Each hydrogen atom now has 2 electrons associated with it in what amounts to a completed valence shell. Two or more atoms held together by covalent bonds constitute a **molecule**. In this case, the example is a hydrogen molecule.



▲ **Figure 2.11 Formation of a covalent bond.**

Electron sharing can be depicted using element symbols, with dots representing the outermost electrons. You have probably seen such diagrams, called Lewis dot structures, in your chemistry book. The Lewis dot structure for a hydrogen molecule, H:H, is shown in **Figure 2.12a**. We can abbreviate the structure of this molecule as H—H, where the line represents a single covalent bond, or simply a **single bond**—that is, a pair of shared electrons. This notation, which represents both atoms and bonding, is called a **structural formula**. We can abbreviate even further by writing H_2, a **molecular formula** indicating simply that the molecule consists of two atoms of hydrogen.

Oxygen has 6 electrons in its second electron shell and therefore needs 2 more electrons to complete its valence shell. Two oxygen atoms form a molecule by sharing *two* pairs of valence electrons **(Figure 2.12b)**. The atoms are thus joined by what is called a double covalent bond, or **double bond**.



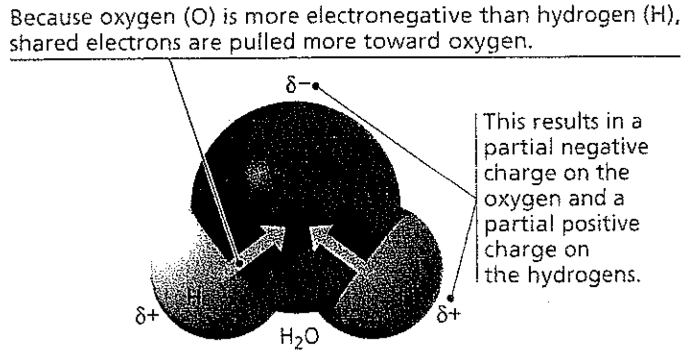
▲ **Figure 2.12 Covalent bonding in four molecules.** A single covalent bond consists of a pair of shared electrons. The number of electrons required to complete an atom's valence shell generally determines how many bonds that atom will form. Four ways of indicating bonds are shown; the space-filling model comes closest to representing the actual shape of the molecule (see also Figure 2.17).

Each atom that can share valence electrons has a bonding capacity corresponding to the number of covalent bonds the atom can form. When the bonds form, they give the atom a full complement of electrons in the valence shell. The bonding capacity of oxygen, for example, is 2. This bonding capacity is called the atom's **valence** and usually equals the number of unpaired electrons required to complete the atom's outermost (valence) shell. See if you can determine the valences of hydrogen, oxygen, nitrogen, and carbon by studying the electron distribution diagrams in Figure 2.9. You can see that the valence of hydrogen is 1; oxygen, 2; nitrogen, 3; and carbon, 4. However, there are more complicated cases, such as phosphorus (P), another element important to life. Phosphorus can have a valence of 3, as we would predict from the presence of 3 unpaired electrons in its valence shell. In biologically important molecules, however, phosphorus can form three single bonds and one double bond. Therefore, it can also have a valence of 5.

The molecules H_2 and O_2 are pure elements rather than compounds because a compound is a combination of two or more *different* elements. Water, with the molecular formula H_2O, is a compound. Two atoms of hydrogen are needed to satisfy the valence of one oxygen atom. **Figure 2.12c** shows the structure of a water molecule. Water is so important to life that Chapter 3 is devoted entirely to its structure and behavior.

Another molecule that is a compound is methane, the main component of natural gas, with the molecular formula CH_4 **(Figure 2.12d)**. It takes four hydrogen atoms, each with a valence of 1, to complement one atom of carbon, with its valence of 4. We will look at many other compounds of carbon in Chapter 4.

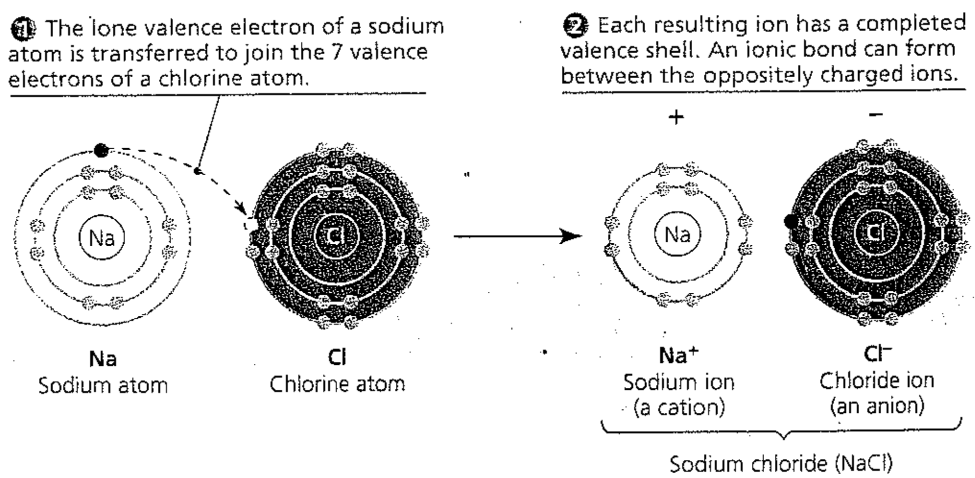
The attraction of a particular kind of atom for the electrons of a covalent bond is called its **electronegativity**. The more electronegative an atom, the more strongly it pulls shared electrons toward itself. In a covalent bond between two atoms of the same element, the outcome of the tug-of-war for common electrons is a standoff; the two atoms are equally electronegative. Such a bond, in which the electrons are shared equally, is a **nonpolar covalent bond**. For example, the covalent bond of H_2 is nonpolar, as is the double bond of O_2. In other compounds, however, where one atom is bonded to a more electronegative atom, the electrons of the bond are not shared equally. This type of bond is called a **polar covalent bond**. Such bonds vary in their polarity, depending on the relative electronegativity of the two atoms. For example, the bonds between the oxygen and hydrogen atoms of a water molecule are quite polar **(Figure 2.13)**. Oxygen is one of the most electronegative of all the elements, attracting shared electrons much more strongly than hydrogen does. In a covalent bond between oxygen and hydrogen, the electrons spend more time near the oxygen nucleus than they do near the hydrogen nucleus. Because electrons have a negative charge, the unequal sharing of electrons in water causes the oxygen atom to have a partial negative charge (indicated by the Greek letter δ with a minus sign, δ−, or "delta minus") and each hydrogen atom to have a partial positive charge (δ+, or "delta plus"). In contrast, the individual bonds of methane (CH_4) are much less polar because carbon and hydrogen differ much less in electronegativity than do oxygen and hydrogen.



▲ **Figure 2.13 Polar covalent bonds in a water molecule.**

Ionic Bonds

In some cases, two atoms are so unequal in their attraction for valence electrons that the more electronegative atom strips an electron completely away from its partner. This is what happens when an atom of sodium ($_{11}Na$) encounters an atom of chlorine ($_{17}Cl$) **(Figure 2.14)**. A sodium atom has a total of 11 electrons,



▲ **Figure 2.14 Electron transfer and ionic bonding.** The attraction between oppositely charged atoms, or ions, is an ionic bond. An ionic bond can form between any two oppositely charged ions, even if they have not been formed by transfer of an electron from one to the other.

with its single valence electron in the third electron shell. A chlorine atom has a total of 17 electrons, with 7 electrons in its valence shell. When these two atoms meet, the lone valence electron of sodium is transferred to the chlorine atom, and both atoms end up with their valence shells complete. (Because sodium no longer has an electron in the third shell, the second shell is now the valence shell.)

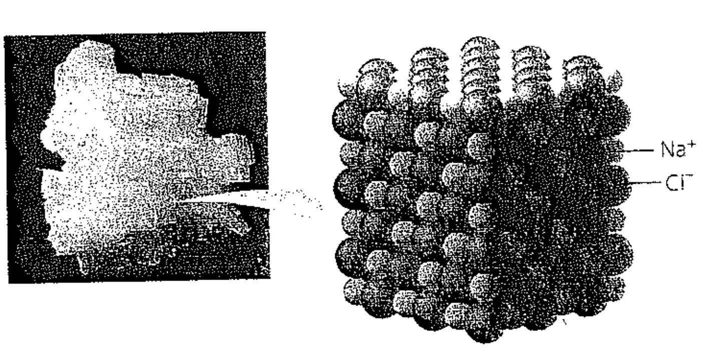
The electron transfer between the two atoms moves one unit of negative charge from sodium to chlorine. Sodium, now with 11 protons but only 10 electrons, has a net electrical charge of 1+. A charged atom (or molecule) is called an **ion**. When the charge is positive, the ion is specifically called a **cation**; the sodium atom has become a cation. Conversely, the chlorine atom, having gained an extra electron, now has 17 protons and 18 electrons, giving it a net electrical charge of 1−. It has become a chloride ion—an **anion**, or negatively charged ion. Because of their opposite charges, cations and anions attract each other; this attraction is called an **ionic bond**. The transfer of an electron is not the formation of a bond; rather, it allows a bond to form because it results in two ions. Any two ions of opposite charge can form an ionic bond. The ions do not need to have acquired their charge by an electron transfer with each other.

Compounds formed by ionic bonds are called **ionic compounds**, or **salts**. We know the ionic compound sodium chloride (NaCl) as table salt (**Figure 2.15**). Salts are often found in nature as crystals of various sizes and shapes. Each salt crystal is an aggregate of vast numbers of cations and anions bonded by their electrical attraction and arranged in a three-dimensional lattice. Unlike a covalent compound, which consists of molecules having a definite size and number of atoms, an ionic compound does not consist of molecules in the same sense. The formula for an ionic compound, such as NaCl, indicates only the ratio of elements in a crystal of the salt. "NaCl" by itself is not a molecule.

Not all salts have equal numbers of cations and anions. For example, the ionic compound magnesium chloride ($MgCl_2$) has two chloride ions for each magnesium ion. Magnesium ($_{12}Mg$) must lose 2 outer electrons if the atom is to have a complete valence shell, so it tends to become a cation with a net charge of 2+ (Mg^{2+}). One magnesium cation can therefore form ionic bonds with two chloride anions.

The term *ion* also applies to entire molecules that are electrically charged. In the salt ammonium chloride (NH_4Cl), for instance, the anion is a single chloride ion (Cl^-), but the cation is ammonium (NH_4^+), a nitrogen atom with four covalently bonded hydrogen atoms. The whole ammonium ion has an electrical charge of 1+ because it is 1 electron short.

Environment affects the strength of ionic bonds. In a dry salt crystal, the bonds are so strong that it takes a hammer and chisel to break enough of them to crack the crystal in two. If the same salt crystal is dissolved in water, however, the ionic bonds are much weaker because each ion is partially shielded by its interactions with water molecules. Most drugs are manufactured as salts because they are quite stable when dry but can dissociate easily in water. In the next chapter, you will learn how water dissolves salts.



▲ **Figure 2.15 A sodium chloride crystal.** The sodium ions (Na^+) and chloride ions (Cl^-) are held together by ionic bonds. The formula NaCl tells us that the ratio of Na^+ to Cl^- is 1:1.

Weak Chemical Bonds

In organisms, most of the strongest chemical bonds are covalent bonds, which link atoms to form a cell's molecules. But weaker bonding within and between molecules is also indispensable in the cell, contributing greatly to the emergent properties of life. Most important large biological molecules are held in their functional form by weak bonds. In addition, when two molecules in the cell make contact, they may adhere temporarily by weak bonds. The reversibility of weak bonding can be an advantage: Two molecules can come together, respond to one another in some way, and then separate.

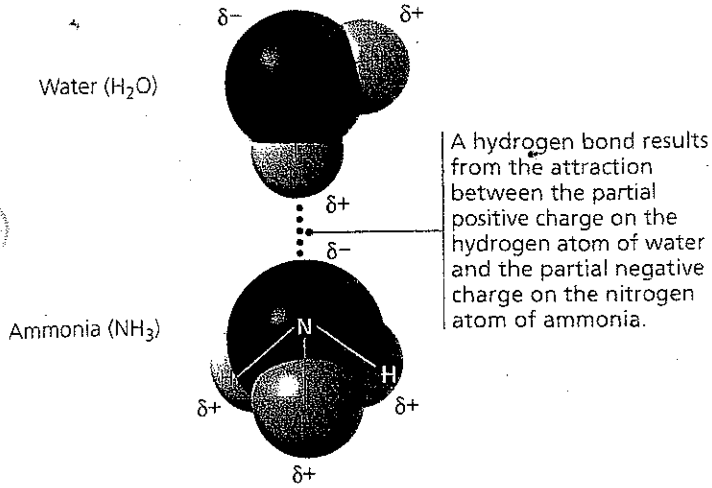
Certain types of weak chemical bonds are important in organisms. One is the ionic bond as it exists between ions dissociated in water, which we just discussed. Another type of weak bond, known as a hydrogen bond, is also crucial to life.

Hydrogen Bonds

Among the various kinds of weak chemical bonds, hydrogen bonds are so important in the chemistry of life that they deserve special attention. A **hydrogen bond** forms when a hydrogen atom covalently bonded to one electronegative atom is also attracted to another electronegative atom. In living cells, the electronegative partners are usually oxygen or nitrogen atoms. Refer to **Figure 2.16** to examine the simple case of hydrogen bonding between water (H_2O) and ammonia (NH_3). In the next chapter, we'll see how the hydrogen bonds between water molecules allow some insects to walk on water.

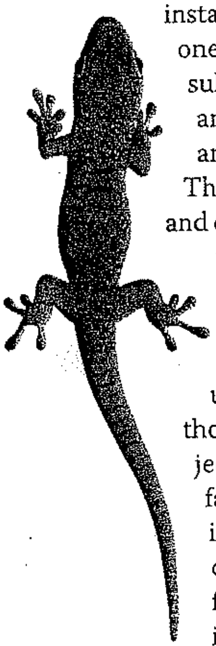
Van der Waals Interactions

Even a molecule with nonpolar covalent bonds may have positively and negatively charged regions. Electrons are not always symmetrically distributed in such a molecule; at any



▲ **Figure 2.16 A hydrogen bond.**

DRAW IT *Draw five water molecules using structural formulas and indicating partial charges, and show how they can make hydrogen bonds with each other.*

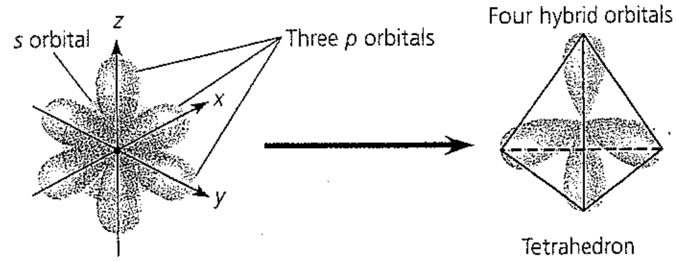


instant, they may accumulate by chance in one part of the molecule or another. The results are ever-changing regions of positive and negative charge that enable all atoms and molecules to stick to one another. These **van der Waals interactions** are weak and occur only when atoms and molecules are very close together. In spite of their weakness, van der Waals interactions were recently shown to be responsible for the ability of a gecko lizard (left) to walk up a wall. Each gecko toe has hundreds of thousands of tiny hairs, with multiple projections at the hair's tip that increase surface area. Apparently, the van der Waals interactions between the hair tip molecules and the molecules of the wall's surface are so numerous that despite their individual weakness, together they can support the gecko's body weight.

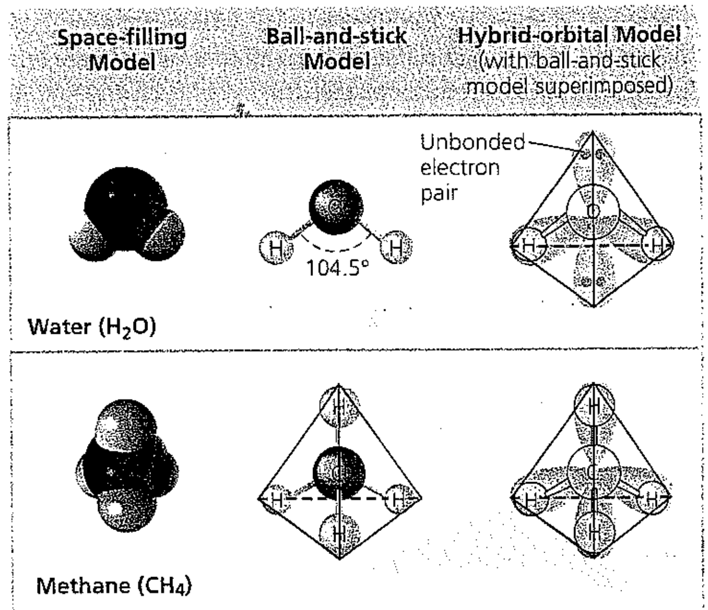
Van der Waals interactions, hydrogen bonds, ionic bonds in water, and other weak bonds may form not only between molecules but also between different regions of a single large molecule, such as a protein. Although these bonds are individually weak, their cumulative effect is to reinforce the three-dimensional shape of a large molecule. You will learn more about the very important biological roles of weak bonds in Chapter 5.

Molecular Shape and Function

A molecule has a characteristic size and shape. The precise shape of a molecule is usually very important to its function in the living cell.



(a) Hybridization of orbitals. The single *s* and three *p* orbitals of a valence shell involved in covalent bonding combine to form four teardrop-shaped hybrid orbitals. These orbitals extend to the four corners of an imaginary tetrahedron (outlined in red).



(b) Molecular-shape models. Three models representing molecular shape are shown for water and methane. The positions of the hybrid orbitals determine the shapes of the molecules.

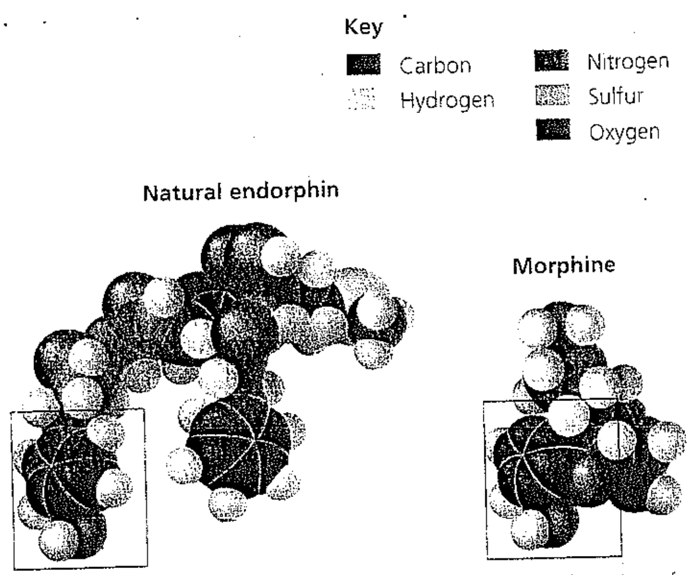
▲ **Figure 2.17 Molecular shapes due to hybrid orbitals.**

A molecule consisting of two atoms, such as H_2 or O_2, is always linear, but molecules with more than two atoms have more complicated shapes. These shapes are determined by the positions of the atoms' orbitals. When an atom forms covalent bonds, the orbitals in its valence shell rearrange. For atoms with valence electrons in both *s* and *p* orbitals (review Figure 2.10), the single *s* and three *p* orbitals hybridize to form four new hybrid orbitals shaped like identical teardrops extending from the region of the atomic nucleus **(Figure 2.17a)**. If we connect the larger ends of the teardrops with lines, we have the outline of a geometric shape called a tetrahedron, similar to a pyramid.

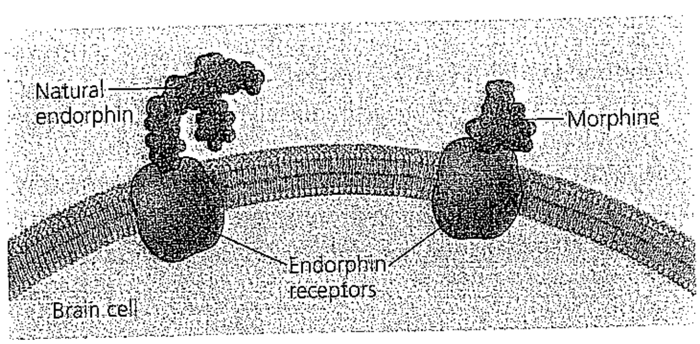
For the water molecule (H_2O), two of the hybrid orbitals in the oxygen atom's valence shell are shared with hydrogen atoms **(Figure 2.17b)**. The result is a molecule shaped roughly like a V, with its two covalent bonds spread apart at an angle of 104.5°.

The methane molecule (CH_4) has the shape of a completed tetrahedron because all four hybrid orbitals of carbon are shared with hydrogen atoms (see Figure 2.17b). The nucleus of the carbon is at the center, with its four covalent bonds radiating to hydrogen nuclei at the corners of the tetrahedron. Larger molecules containing multiple carbon atoms, including many of the molecules that make up living matter, have more complex overall shapes. However, the tetrahedral shape of a carbon atom bonded to four other atoms is often a repeating motif within such molecules.

Molecular shape is crucial in biology because it determines how biological molecules recognize and respond to one another with specificity. Only molecules with complementary shapes can form weak bonds with each other. We can see this specificity in the effects of opiates, drugs derived from opium. Opium's narcotic effects have been known since ancient times. During the 1800s, morphine was isolated from opium, and heroin was synthesized from morphine. These opiates relieve pain and alter mood by binding to specific receptor molecules on the surface of brain cells. Why would brain cells carry receptors for opiates, compounds not made by our bodies? The discovery of endorphins in 1975 answered this question. Endorphins are signaling molecules made by the pituitary gland that bind to the receptors, relieving pain and producing euphoria during times of stress, such as intense exercise. It turns out that opiates have shapes similar to endorphins and mimic them by binding to endorphin receptors in the brain. That is why opiates and endorphins have similar effects (**Figure 2.18**). The role of molecular shape in brain chemistry illustrates the relationship between structure and function, one of biology's unifying themes.



(a) Structures of endorphin and morphine. The boxed portion of the endorphin molecule (left) binds to receptor molecules on target cells in the brain. The boxed portion of the morphine molecule (right) is a close match.



(b) Binding to endorphin receptors. Both endorphin and morphine can bind to endorphin receptors on the surface of a brain cell.

▲ **Figure 2.18 A molecular mimic.** Morphine affects pain perception and emotional state by mimicking the brain's natural endorphins.

CONCEPT CHECK 2.3

1. Why does the following structure fail to make sense chemically?

$$H{-}C{=}C{-}H$$

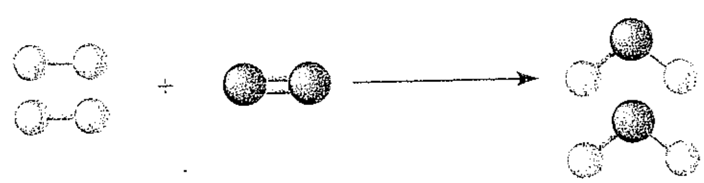
2. Explain what holds together the atoms in a crystal of magnesium chloride ($MgCl_2$).
3. **WHAT IF?** If you were a pharmaceutical researcher, why would you want to learn the three-dimensional shapes of naturally occurring signaling molecules?

For suggested answers, see Appendix A.

CONCEPT 2.4

Chemical reactions make and break chemical bonds

The making and breaking of chemical bonds, leading to changes in the composition of matter, are called **chemical reactions**. An example is the reaction between hydrogen and oxygen that forms water:



$$2\,H_2 \quad + \quad O_2 \quad \longrightarrow \quad 2\,H_2O$$

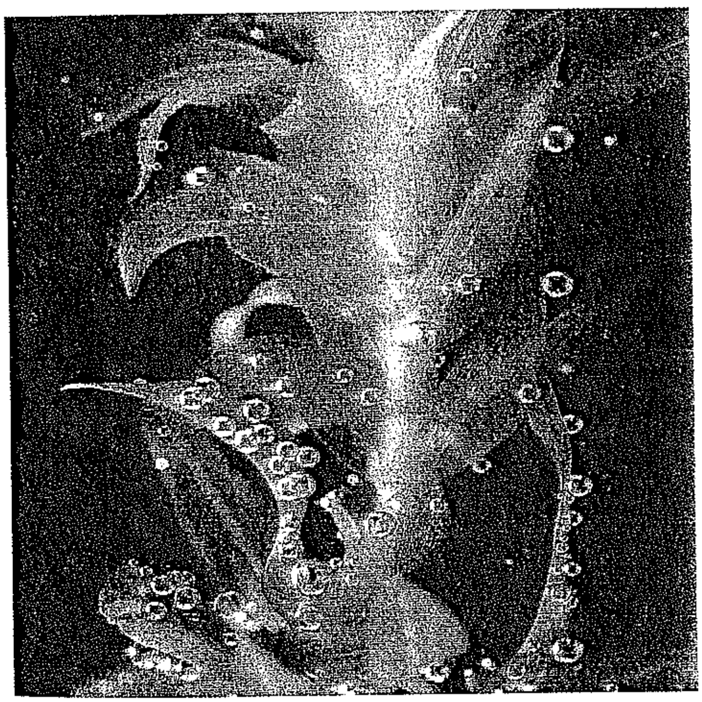
Reactants — Reaction — Products

This reaction breaks the covalent bonds of H_2 and O_2 and forms the new bonds of H_2O. When we write a chemical reaction, we use an arrow to indicate the conversion of the starting materials, called the **reactants**, to the **products**. The coefficients indicate the number of molecules involved; for example, the coefficient 2 in front of the H_2 means that the reaction starts with two molecules of hydrogen. Notice that all atoms of the reactants must be accounted for in the products. Matter is conserved in a chemical reaction: Reactions cannot create or destroy matter but can only rearrange it.

Photosynthesis, which takes place within the cells of green plant tissues, is a particularly important example of how chemical reactions rearrange matter. Humans and other animals ultimately depend on photosynthesis for food and oxygen, and this process is at the foundation of almost all ecosystems. The following chemical shorthand summarizes the process of photosynthesis:

$$6\ CO_2 + 6\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ O_2$$

The raw materials of photosynthesis are carbon dioxide (CO_2), which is taken from the air, and water (H_2O), which is absorbed from the soil. Within the plant cells, sunlight powers the conversion of these ingredients to a sugar called glucose ($C_6H_{12}O_6$) and oxygen molecules (O_2), a by-product that the plant releases into the surroundings (**Figure 2.19**). Although photosynthesis is actually a sequence of many chemical reactions, we still end up with the same number and kinds of atoms we had when we started. Matter has simply been rearranged, with an input of energy provided by sunlight.



▲ Figure 2.19 **Photosynthesis: a solar-powered rearrangement of matter.** *Elodea*, a freshwater plant, produces sugar by rearranging the atoms of carbon dioxide and water in the chemical process known as photosynthesis, which is powered by sunlight. Much of the sugar is then converted to other food molecules. Oxygen gas (O_2) is a by-product of photosynthesis; notice the bubbles of oxygen escaping from the leaves in the photo.

Explain how this photo relates to the reactants and products in the equation for photosynthesis given in the above text. (You will learn more about photosynthesis in Chapter 10.)

All chemical reactions are reversible, with the products of the forward reaction becoming the reactants for the reverse reaction. For example, hydrogen and nitrogen molecules can combine to form ammonia, but ammonia can also decompose to regenerate hydrogen and nitrogen:

$$3\ H_2 + N_2 \rightleftharpoons 2\ NH_3$$

The two opposite-headed arrows indicate that the reaction is reversible.

One of the factors affecting the rate of a reaction is the concentration of reactants. The greater the concentration of reactant molecules, the more frequently they collide with one another and have an opportunity to react and form products. The same holds true for products. As products accumulate, collisions resulting in the reverse reaction become more frequent. Eventually, the forward and reverse reactions occur at the same rate, and the relative concentrations of products and reactants stop changing. The point at which the reactions offset one another exactly is called **chemical equilibrium**. This is a dynamic equilibrium; reactions are still going on, but with no net effect on the concentrations of reactants and products. Equilibrium does *not* mean that the reactants and products are equal in concentration, but only that their concentrations have stabilized at a particular ratio. The reaction involving ammonia reaches equilibrium when ammonia decomposes as rapidly as it forms. In some chemical reactions, the equilibrium point may lie so far to the right that these reactions go essentially to completion; that is, virtually all the reactants are converted to products.

We will return to the subject of chemical reactions after more detailed study of the various types of molecules that are important to life. In the next chapter, we focus on water, the substance in which all the chemical processes of organisms occur.

CONCEPT CHECK 2.4

1. Refer to the reaction between hydrogen and oxygen that forms water, shown with ball-and-stick models on page 42. Draw the Lewis dot structures representing this reaction.
2. Which types of chemical reactions occur faster at equilibrium, the formation of products from reactants, or reactants from products?
3. WHAT IF? Write an equation that uses the products of photosynthesis as reactants and uses the reactants as products. Add energy as another product. This new equation describes a process that occurs in your cells. Describe this equation in words. How does this equation relate to breathing?

For suggested answers, see Appendix A.

Chapter 2 Review

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SUMMARY OF KEY CONCEPTS

CONCEPT 2.1

Matter consists of chemical elements in pure form and in combinations called compounds (pp. 31–32)

- **Elements and Compounds** Elements cannot be broken down chemically to other substances. A compound contains two or more different elements in a fixed ratio.
- **Essential Elements of Life** Carbon, oxygen, hydrogen, and nitrogen make up approximately 96% of living matter.

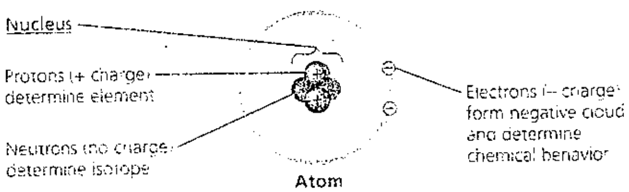
MEDIA

Investigation How Are Space Rocks Analyzed for Signs of Life?

CONCEPT 2.2

An element's properties depend on the structure of its atoms (pp. 32–37)

- **Subatomic Particles** An atom, the smallest unit of an element, has the following components:



- **Atomic Number and Atomic Mass** An electrically neutral atom has equal numbers of electrons and protons; the number of protons determines the atomic number. The atomic mass is measured in daltons and is roughly equal to the sum of protons plus neutrons.
- **Isotopes** Isotopes of an element differ from each other in neutron number and therefore mass. Unstable isotopes give off particles and energy as radioactivity.
- **The Energy Levels of Electrons** In an atom, electrons occupy specific energy shells; the electrons in a shell have a characteristic energy level.
- **Electron Distribution and Chemical Properties** Electron distribution in shells determines the chemical behavior of an atom. An atom that has an incomplete valence shell is reactive.
- **Electron Orbitals** Electrons exist in orbitals, three-dimensional spaces with specific shapes that are components of electron shells.

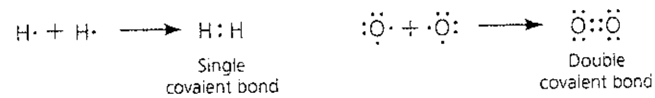
MEDIA

Activity Structure of the Atomic Nucleus
Activity Electron Arrangement
Activity Build an Atom

CONCEPT 2.3

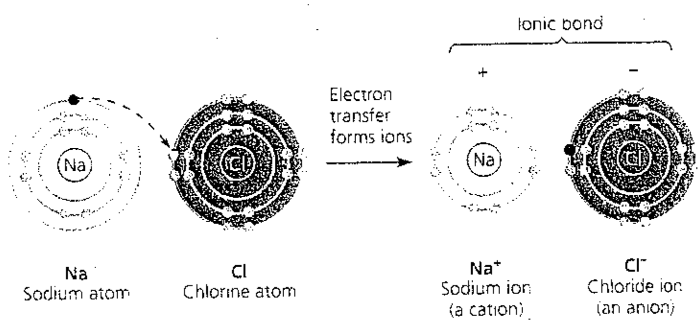
The formation and function of molecules depend on chemical bonding between atoms (pp. 38–42)

- **Covalent Bonds** Chemical bonds form when atoms interact and complete their valence shells. Covalent bonds form when pairs of electrons are shared.



Molecules consist of two or more covalently bonded atoms. Electrons of a polar covalent bond are pulled closer to the more electronegative atom. If both atoms are the same, they have the same electronegativity, and the covalent bond is nonpolar.

- **Ionic Bonds**



- **Weak Chemical Bonds** A hydrogen bond is an attraction between a hydrogen atom carrying a partial positive charge ($\delta+$) and an electronegative atom ($\delta-$). Van der Waals interactions occur between transiently positive and negative regions of molecules. Weak bonds reinforce the shapes of large molecules and help molecules adhere to each other.
- **Molecular Shape and Function** A molecule's shape is determined by the positions of its atoms' valence orbitals. Covalent bonds result in hybrid orbitals, which are responsible for the shapes of H_2O, CH_4, and many more complex biological molecules. Shape is usually the basis for the recognition of one biological molecule by another.

MEDIA

Activity Covalent Bonds
Activity Nonpolar and Polar Molecules
Activity Ionic Bonds
Activity Hydrogen Bonds

CONCEPT 2.4

Chemical reactions make and break chemical bonds (pp. 42–43)

- Chemical reactions change reactants into products while conserving matter. All chemical reactions are theoretically reversible. Chemical equilibrium is reached when the forward and reverse reaction rates are equal.

TESTING YOUR KNOWLEDGE

SELF-QUIZ

1. In the term *trace element*, the modifier *trace* means
   a. the element is required in very small amounts.
   b. the element can be used as a label to trace atoms through an organism's metabolism.
   c. the element is very rare on Earth.
   d. the element enhances health but is not essential for the organism's long-term survival.
   e. the element passes rapidly through the organism.

2. Compared with ^{31}P, the radioactive isotope ^{32}P has
   a. a different atomic number.
   b. one more neutron.
   c. one more proton.
   d. one more electron.
   e. a different charge.

3. Atoms can be represented by simply listing the number of protons, neutrons, and electrons—for example, $2p^+$; $2n^0$; $2e^-$ for helium. Which one of the following lists represents the ^{18}O isotope of oxygen?
   a. $6p^+$; $8n^0$; $6e^-$
   b. $8p^+$; $10n^0$; $8e^-$
   c. $9p^+$; $9n^0$; $9e^-$
   d. $7p^+$; $2n^0$; $9e^-$
   e. $10p^+$; $8n^0$; $9e^-$

4. The atomic number of sulfur is 16. Sulfur combines with hydrogen by covalent bonding to form a compound, hydrogen sulfide. Based on the number of valence electrons in a sulfur atom, predict the molecular formula of the compound:
   a. HS b. HS_2 c. H_2S d. H_3S_2 e. H_4S

5. The reactivity of an atom arises from
   a. the average distance of the outermost electron shell from the nucleus.
   b. the existence of unpaired electrons in the valence shell.
   c. the sum of the potential energies of all the electron shells.
   d. the potential energy of the valence shell.
   e. the energy difference between the *s* and *p* orbitals.

6. Which statement is true of all atoms that are anions?
   a. The atom has more electrons than protons.
   b. The atom has more protons than electrons.
   c. The atom has fewer protons than does a neutral atom of the same element.
   d. The atom has more neutrons than protons.
   e. The net charge is 1−.

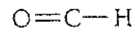
7. What coefficients must be placed in the following blanks so that all atoms are accounted for in the products?

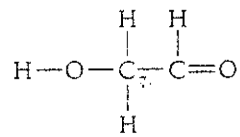
$$C_6H_{12}O_6 \longrightarrow \_\_\_C_2H_6O + \_\_\_CO_2$$

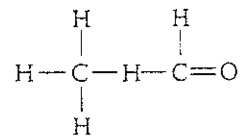
   a. 1; 2 b. 2; 2 c. 1; 3 d. 1; 1 e. 3; 1

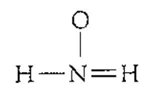
8. Which of the following statements correctly describes any chemical reaction that has reached equilibrium?
   a. The concentrations of products and reactants are equal.
   b. The rates of the forward and reverse reactions are equal.
   c. Both forward and reverse reactions have halted.
   d. The reaction is now irreversible.
   e. No reactants remain.

9. DRAW IT Draw Lewis structures for each hypothetical molecule shown below, using the correct number of valence electrons for each atom. Determine which molecule makes sense because each atom has a complete valence shell and each bond has the correct number of electrons. Explain what makes the other molecules nonsensical, considering the number of bonds each type of atom can make.

a. 

b. 

c. 

d. 

For Self-Quiz answers, see Appendix A.

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EVOLUTION CONNECTION

10. The percentages of naturally occurring elements making up the human body (see Table 2.1) are similar to the percentages of these elements found in other organisms. How could you account for this similarity among organisms?

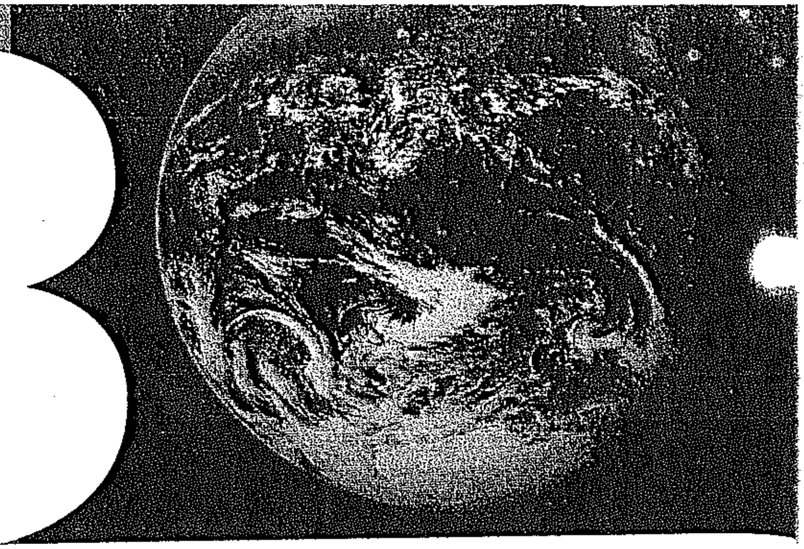
SCIENTIFIC INQUIRY

11. Female silkworm moths (*Bombyx mori*) attract males by emitting chemical signals that spread through the air. A male hundreds of meters away can detect these molecules and fly toward their source. The sensory organs responsible for this behavior are the comblike antennae visible in the photograph here. Each filament of an antenna is equipped with thousands of receptor cells that detect the sex attractant. Based on what you learned in this chapter, propose a hypothesis to account for the ability of the male moth to detect a specific molecule in the presence of many other molecules in the air. What predictions does your hypothesis make? Design an experiment to test one of these predictions.

SCIENCE, TECHNOLOGY, AND SOCIETY

12. While waiting at an airport, Neil Campbell once overheard this claim: "It's paranoid and ignorant to worry about industry or agriculture contaminating the environment with their chemical wastes. After all, this stuff is just made of the same atoms that were already present in our environment." How would you counter this argument?

3 Water and the Fitness of the Environment



▲ **Figure 3.1 Why does the abundance of water allow life to exist on the planet Earth?**

KEY CONCEPTS

3.1 **The polarity of water molecules results in hydrogen bonding**

3.2 **Four emergent properties of water contribute to Earth's fitness for life**

3.3 **Acidic and basic conditions affect living organisms**

OVERVIEW

The Molecule That Supports All of Life

As astronomers study newly discovered planets orbiting distant stars, they hope to find evidence of water on these far-off celestial bodies, for water is the substance that makes possible life as we know it here on Earth. All organisms familiar to us are made mostly of water and live in an environment dominated by water. Water is the biological medium here on Earth, and possibly on other planets as well.

Three-quarters of Earth's surface is submerged in water (**Figure 3.1**). Although most of this water is in liquid form, water is also present on Earth as ice and vapor. Water is the only common substance to exist in the natural environment in all three physical states of matter: solid, liquid, and gas. The abundance of water is a major reason Earth is habitable. In a classic book called *The Fitness of the Environment,* ecologist Lawrence Henderson highlights the importance of water to life. While acknowledging that life adapts to its environment through natural selection, Henderson emphasizes that for life to exist at all, the environment must first be a suitable abode.

Life on Earth began in water and evolved there for 3 billion years before spreading onto land. Modern life, even terrestrial (land-dwelling) life, remains tied to water. All living organisms require water more than any other substance. Human beings, for example, can survive for quite a few weeks without food, but only a week or so without water. Molecules of water participate in many chemical reactions necessary to sustain life. Most cells are surrounded by water, and cells themselves are about 70–95% water.

What properties of the simple water molecule allow it to function as a support to all living organisms? In this chapter, you will learn how the structure of a water molecule allows it to interact with other molecules, including other water molecules. This ability leads to unique emergent properties that support and maintain living systems on our planet. Your objective in this chapter is to develop a conceptual understanding of how water contributes to the fitness of Earth for life.

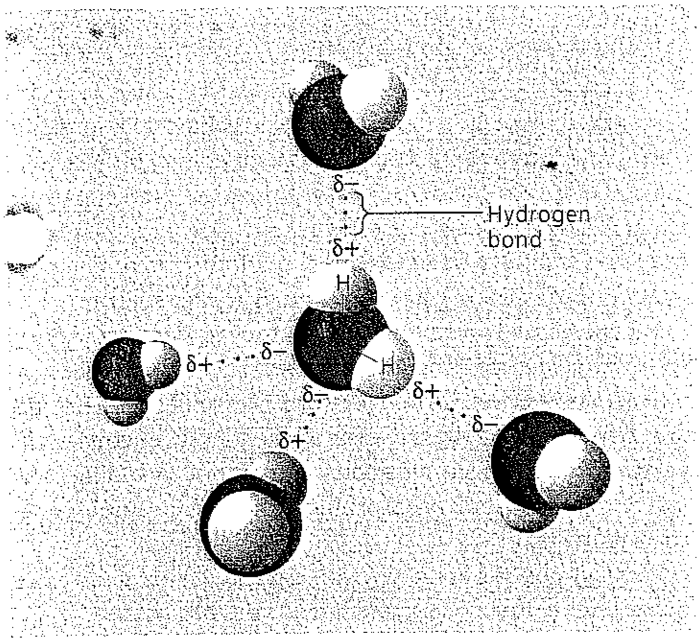
CONCEPT 3.1

The polarity of water molecules results in hydrogen bonding

Water is so common that it is easy to overlook the fact that it is an exceptional substance with many extraordinary qualities. Following the theme of emergent properties, we can trace water's unique behavior to the structure and interactions of its molecules.

Studied in isolation, the water molecule is deceptively simple. It is shaped something like a wide V, with its two hydrogen atoms joined to the oxygen atom by single covalent bonds. Because oxygen is more electronegative than hydrogen, the electrons of the covalent bonds spend more time closer to oxygen than to hydrogen; in other words, they are polar covalent bonds (see Figure 2.13). This unequal distribution of electrons makes water a **polar molecule**, meaning that the two ends of the molecule have opposite charges: The oxygen region of the molecule has a partial negative charge ($\delta-$), and the hydrogens have a partial positive charge ($\delta+$).

The anomalous properties of water arise from attractions between its polar molecules: The slightly positive hydrogen of

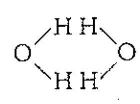


▲ **Figure 3.2 Hydrogen bonds between water molecules.** The charged regions of a polar water molecule are attracted to oppositely charged parts of neighboring molecules. Each molecule can hydrogen-bond to multiple partners, and these associations are constantly changing.

one molecule is attracted to the slightly negative oxygen of a nearby molecule. The two molecules are thus held together by a hydrogen bond (**Figure 3.2**). When water is in its liquid form, its hydrogen bonds are very fragile, each about 1/20 as ɔng as a covalent bond. The hydrogen bonds form, break, and re-form with great frequency. Each lasts only a few trillionths of a second, but the molecules are constantly forming new hydrogen bonds with a succession of partners. Therefore, at any instant, a substantial percentage of all the water molecules are hydrogen-bonded to their neighbors. The extraordinary qualities of water are emergent properties resulting from the hydrogen bonding that orders molecules into a higher level of structural organization.

CONCEPT CHECK 3.1

1. What is electronegativity, and how does it affect interactions between water molecules?
2. Why is it unlikely that two neighboring water molecules would be arranged like this?



3. **WHAT IF?** What would be the effect on the properties of the water molecule if oxygen and hydrogen had equal electronegativity?

For suggested answers, see Appendix A.

CONCEPT 3.2

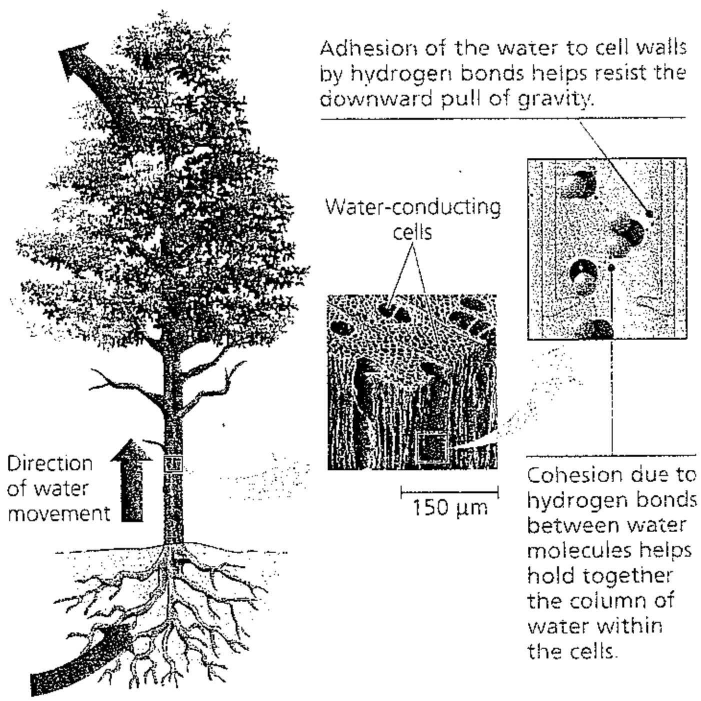
Four emergent properties of water contribute to Earth's fitness for life

We will examine four emergent properties of water that contribute to Earth's suitability as an environment for life: cohesive behavior, ability to moderate temperature, expansion upon freezing, and versatility as a solvent.

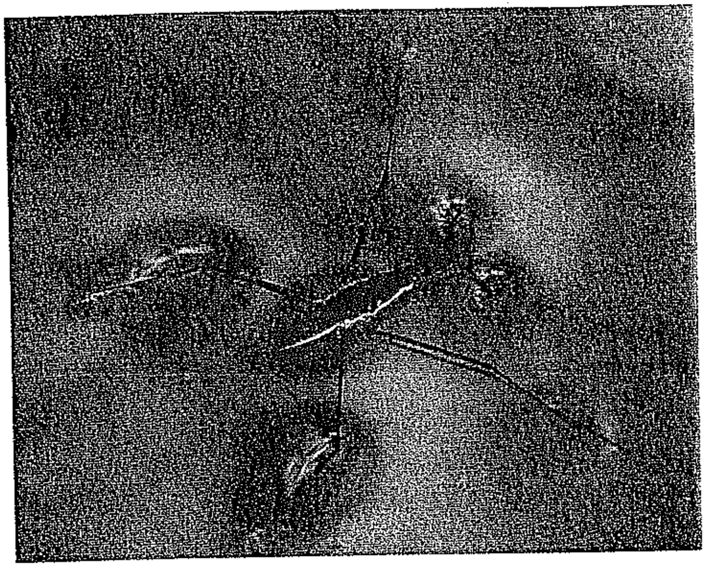
Cohesion

Water molecules stay close to each other as a result of hydrogen bonding. Although the arrangement of molecules in a sample of liquid water is constantly changing, at any given moment many of the molecules are linked by multiple hydrogen bonds. These linkages make water more structured than most other liquids. Collectively, the hydrogen bonds hold the substance together, a phenomenon called **cohesion.**

Cohesion due to hydrogen bonding contributes to the transport of water and dissolved nutrients against gravity in plants (**Figure 3.3**). Water from the roots reaches the leaves through a network of water-conducting cells. As water evaporates from a leaf, hydrogen bonds cause water molecules leaving the veins to tug on molecules farther down, and the upward pull is transmitted through the water-conducting cells all the way to the roots. **Adhesion,** the clinging of one substance to



▲ **Figure 3.3 Water transport in plants.** Evaporation from leaves pulls water upward from the roots through water-conducting cells. Because of the properties of cohesion and adhesion, the tallest trees can transport water more than 100 m upward—approximately one-quarter the height of the Empire State Building in New York City.



▲ **Figure 3.4 Walking on water.** The high surface tension of water, resulting from the collective strength of its hydrogen bonds, allows the water strider to walk on the surface of a pond.

another, also plays a role. Adhesion of water to cell walls by hydrogen bonds helps counter the downward pull of gravity (see Figure 3.3).

Related to cohesion is **surface tension**, a measure of how difficult it is to stretch or break the surface of a liquid. Water has a greater surface tension than most other liquids. At the interface between water and air is an ordered arrangement of water molecules, hydrogen-bonded to one another and to the water below. This makes the water behave as though coated with an invisible film. You can observe the surface tension of water by slightly overfilling a drinking glass; the water will stand above the rim. In a more biological example, some animals can stand, walk, or run on water without breaking the surface (**Figure 3.4**).

Moderation of Temperature

Water moderates air temperature by absorbing heat from air that is warmer and releasing the stored heat to air that is cooler. Water is effective as a heat bank because it can absorb or release a relatively large amount of heat with only a slight change in its own temperature. To understand this capability of water, we must first look briefly at heat and temperature.

Heat and Temperature

Anything that moves has **kinetic energy**, the energy of motion. Atoms and molecules have kinetic energy because they are always moving, although not necessarily in any particular direction. The faster a molecule moves, the greater its kinetic energy. **Heat** is a form of energy. For a given body of matter, the amount of heat is a measure of the matter's *total* kinetic energy due to motion of its molecules; thus, heat depends in part on the matter's volume. Although heat is related to temperature, they are not the same thing. **Temperature** is a measure of heat intensity that represents the *average* kinetic energy of the molecules, regardless of volume. When water is heated in a coffeemaker, the average speed of the molecules increases, and the thermometer records this as a rise in temperature of the liquid. The amount of heat also increases in this case. Note, however, that although the pot of coffee has a much higher temperature than, say, the water in a swimming pool, the swimming pool contains more heat because of its much greater volume.

Whenever two objects of different temperature are brought together, heat passes from the warmer to the cooler object until the two are the same temperature. Molecules in the cooler object speed up at the expense of the kinetic energy of the warmer object. An ice cube cools a drink not by adding coldness to the liquid, but by absorbing heat from the liquid as the ice itself melts.

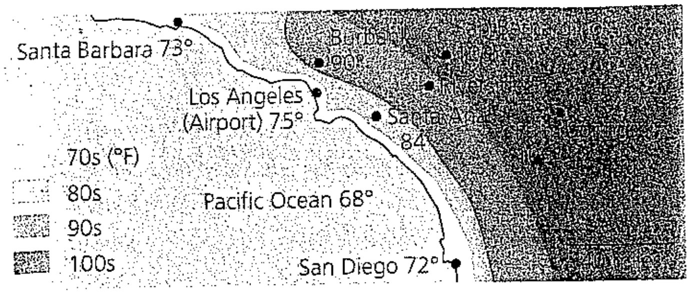
Throughout this book, we will use the **Celsius scale** to indicate temperature (Celsius degrees are abbreviated °C). At sea level, water freezes at 0°C and boils at 100°C. The temperature of the human body averages 37°C, and comfortable room temperature is about 20–25°C.

One convenient unit of heat used in this book is the **calorie (cal)**. A calorie is the amount of heat it takes to raise the temperature of 1 g of water by 1°C. Conversely, a calorie is also the amount of heat that 1 g of water releases when it cools by 1°C. A **kilocalorie (kcal)**, 1,000 cal, is the quantity of heat required to raise the temperature of 1 kilogram (kg) of water by 1°C. (The "calories" on food packages are actually kilocalories.) Another energy unit used in this book is the **joule (J)**. One joule equals 0.239 cal; one calorie equals 4.184 J.

Water's High Specific Heat

The ability of water to stabilize temperature stems from its relatively high specific heat. The **specific heat** of a substance is defined as the amount of heat that must be absorbed or lost for 1 g of that substance to change its temperature by 1°C. We already know water's specific heat because we have defined a calorie as the amount of heat that causes 1 g of water to change its temperature by 1°C. Therefore, the specific heat of water is 1 calorie per gram per degree Celsius, abbreviated as 1 cal/g/°C. Compared with most other substances, water has an unusually high specific heat. For example, ethyl alcohol, the type of alcohol in alcoholic beverages, has a specific heat of 0.6 cal/g/°C; that is, only 0.6 cal is required to raise the temperature of 1 g of ethyl alcohol 1°C.

Because of the high specific heat of water relative to other materials, water will change its temperature less when it absorbs or loses a given amount of heat. The reason you can burn your fingers by touching the side of a metal pot on the stove when the water in the pot is still lukewarm is that the specific heat of water is ten times greater than that of iron. In other words, the same amount of heat will raise the temperature of



▲ **Figure 3.5 Effect of a large body of water on climate.** By absorbing or releasing heat, oceans moderate coastal climates. In this example from an August day in Southern California, the relatively cool ocean reduces coastal air temperatures by absorbing heat.

1 g of the iron much faster than the temperature of 1 g of the water. Specific heat can be thought of as a measure of how well a substance resists changing its temperature when it absorbs or releases heat. Water resists changing its temperature; when it does change its temperature, it absorbs or loses a relatively large quantity of heat for each degree of change.

We can trace water's high specific heat, like many of its other properties, to hydrogen bonding. Heat must be absorbed in order to break hydrogen bonds, and heat is released when hydrogen bonds form. A calorie of heat causes a relatively small change in the temperature of water because much of the heat is used to disrupt hydrogen bonds before the water molecules can begin moving faster. And when the temperature of water drops slightly, many additional hydrogen bonds form, releasing a considerable amount of energy in the form of heat.

What is the relevance of water's high specific heat to life on Earth? A large body of water can absorb and store a huge amount of heat from the sun in the daytime and during summer while warming up only a few degrees. And at night and during winter, the gradually cooling water can warm the air. This is the reason coastal areas generally have milder climates than inland regions (**Figure 3.5**). The high specific heat of water also tends to stabilize ocean temperatures, creating a favorable environment for marine life. Thus, because of its high specific heat, the water that covers most of Earth keeps temperature fluctuations on land and in water within limits that permit life. Also, because organisms are made primarily of water, they are more able to resist changes in their own temperature than if they were made of a liquid with a lower specific heat.

Evaporative Cooling

Molecules of any liquid stay close together because they are attracted to one another. Molecules moving fast enough to overcome these attractions can depart the liquid and enter the air as gas. This transformation from a liquid to a gas is called vaporization, or *evaporation*. Recall that the speed of molecular movement varies and that temperature is the *average* kinetic energy of molecules. Even at low temperatures, the speediest molecules can escape into the air. Some evaporation occurs at any temperature; a glass of water at room temperature, for example, will eventually evaporate. If a liquid is heated, the average kinetic energy of molecules increases and the liquid evaporates more rapidly.

Heat of vaporization is the quantity of heat a liquid must absorb for 1 g of it to be converted from the liquid to the gaseous state. For the same reason that water has a high specific heat, it also has a high heat of vaporization relative to most other liquids. To evaporate 1 g of water at 25°C, about 580 cal of heat is needed—nearly double the amount needed to vaporize a gram of alcohol or ammonia. Water's high heat of vaporization is another emergent property caused by hydrogen bonds, which must be broken before the molecules can make their exodus from the liquid.

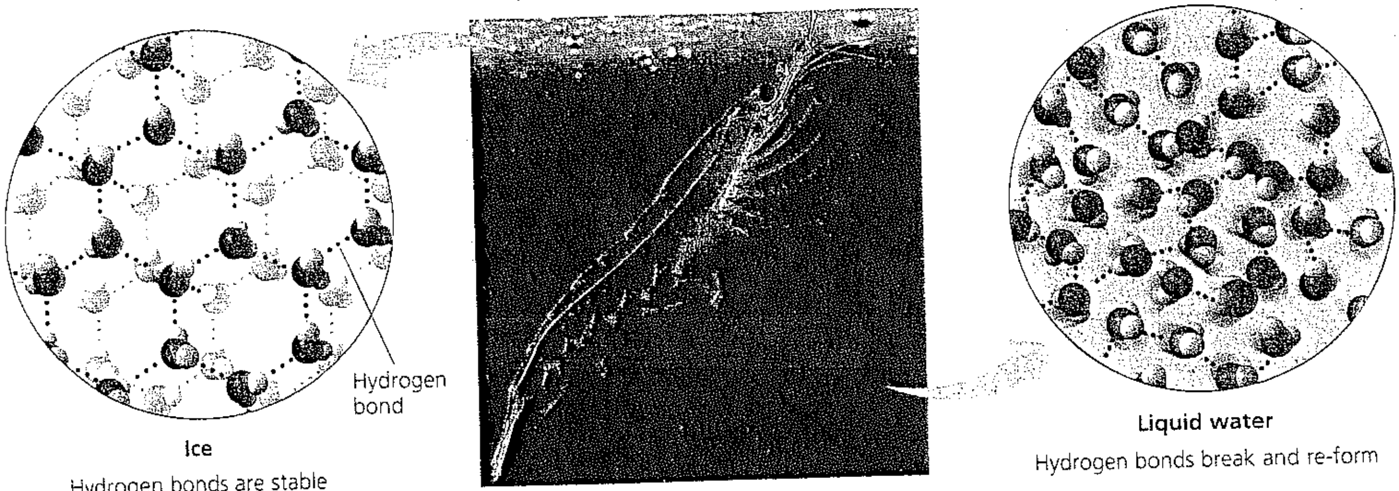
The high amount of energy required to vaporize water has a wide range of effects. On a global scale, for example, it helps moderate Earth's climate. A considerable amount of solar heat absorbed by tropical seas is consumed during the evaporation of surface water. Then, as moist tropical air circulates poleward, it releases heat as it condenses and forms rain. On an organismal level, water's high heat of vaporization accounts for the severity of steam burns. These burns are caused by the heat energy released when steam condenses into liquid on the skin.

As a liquid evaporates, the surface of the liquid that remains behind cools down. This **evaporative cooling** occurs because the "hottest" molecules, those with the greatest kinetic energy, are the most likely to leave as gas. It is as if the hundred fastest runners at a college transferred to another school; the average speed of the remaining students would decline.

Evaporative cooling of water contributes to the stability of temperature in lakes and ponds and also provides a mechanism that prevents terrestrial organisms from overheating. For example, evaporation of water from the leaves of a plant helps keep the tissues in the leaves from becoming too warm in the sunlight. Evaporation of sweat from human skin dissipates body heat and helps prevent overheating on a hot day or when excess heat is generated by strenuous activity. High humidity on a hot day increases discomfort because the high concentration of water vapor in the air inhibits the evaporation of sweat from the body.

Insulation of Bodies of Water by Floating Ice

Water is one of the few substances that are less dense as a solid than as a liquid. In other words, ice floats in liquid water. While other materials contract when they solidify, water expands. The cause of this exotic behavior is, once again, hydrogen bonding. At temperatures above 4°C, water behaves like other liquids, expanding as it warms and contracting as it cools. Water begins to freeze when its molecules are no longer moving vigorously enough to break their hydrogen bonds. As the temperature falls to 0°C, the water becomes locked into a crystalline lattice, each water molecule hydrogen-bonded to



▲ **Figure 3.6 Ice: crystalline structure and floating barrier.** In ice, each molecule is hydrogen-bonded to four neighbors in a three-dimensional crystal. Because the crystal is spacious, ice has fewer molecules than an equal volume of liquid water. In other words, ice is less dense than liquid water. Floating ice becomes a barrier that protects the liquid water below from the colder air. The marine organism shown here is a type of shrimp called krill; it was photographed beneath floating ice in the Antarctic Ocean.

If water did not form hydrogen bonds, what would happen to the shrimp's environment?

four partners (**Figure 3.6**). The hydrogen bonds keep the molecules at "arm's length," far enough apart to make ice about 10% less dense (10% fewer molecules for the same volume) than liquid water at 4°C. When ice absorbs enough heat for its temperature to rise above 0°C, hydrogen bonds between molecules are disrupted. As the crystal collapses, the ice melts, and molecules are free to slip closer together. Water reaches its greatest density at 4°C and then begins to expand as the molecules move faster. Keep in mind, however, that even in liquid water, many of the molecules are connected by hydrogen bonds, though only transiently: The hydrogen bonds are constantly breaking and re-forming.

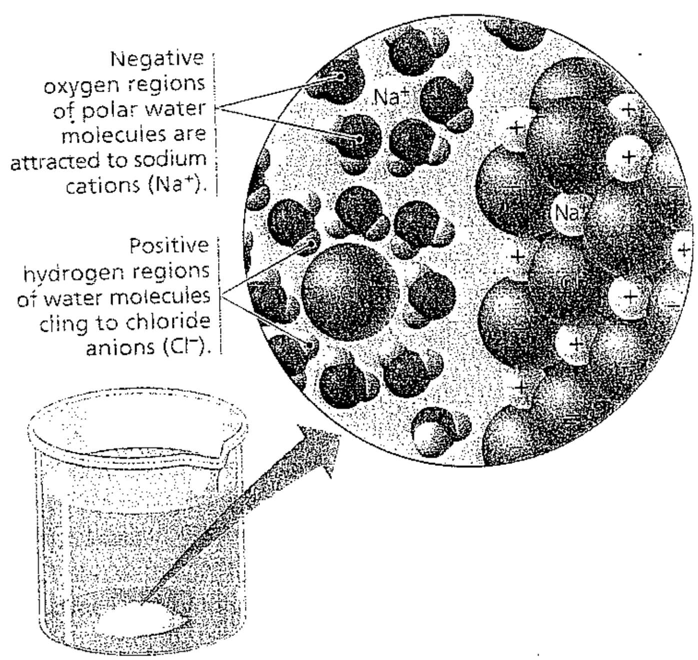
The ability of ice to float because of the expansion of water as it solidifies is an important factor in the fitness of the environment. If ice sank, then eventually all ponds, lakes, and even oceans would freeze solid, making life as we know it impossible on Earth. During summer, only the upper few inches of the ocean would thaw. Instead, when a deep body of water cools, the floating ice insulates the liquid water below, preventing it from freezing and allowing life to exist under the frozen surface, as shown in the photo in Figure 3.6.

The Solvent of Life

A sugar cube placed in a glass of water will dissolve. The glass will then contain a uniform mixture of sugar and water; the concentration of dissolved sugar will be the same everywhere in the mixture. A liquid that is a completely homogeneous mixture of two or more substances is called a **solution**. The dissolving agent of a solution is the **solvent**, and the substance that is dissolved is the **solute**. In this case, water is the solvent and sugar is the solute. An **aqueous solution** is one in which water is the solvent.

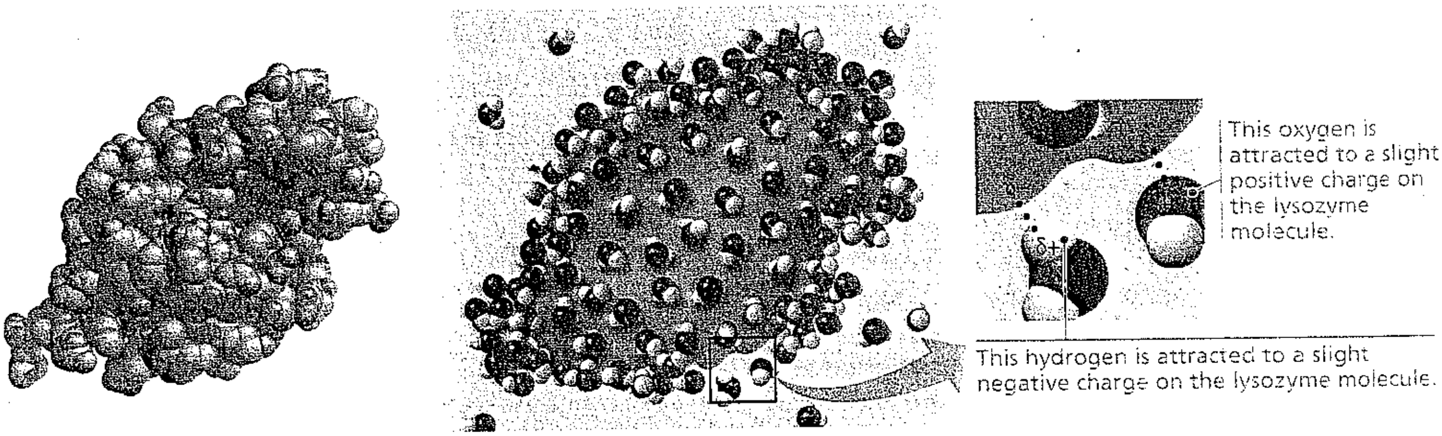
The medieval alchemists tried to find a universal solvent, one that would dissolve anything. They learned that nothing works better than water. However, water is not a universal solvent; if it were, it would dissolve any container in which it was stored, including our cells. But water is a very versatile solvent, a quality we can trace to the polarity of the water molecule.

Suppose, for example, that a spoonful of table salt, the ionic compound sodium chloride (NaCl), is placed in water (**Figure 3.7**). At the surface of each grain, or crystal, of salt, the sodium and chloride ions are exposed to the solvent. These ions and the water molecules have a mutual affinity owing to the attraction between opposite charges. The oxygen



▲ **Figure 3.7 Table salt dissolving in water.** A sphere of water molecules, called a hydration shell, surrounds each solute ion.

What would happen if you heated this solution for a long time?



(a) Lysozyme molecule in a nonaqueous environment

(b) Lysozyme molecule (purple) in an aqueous environment such as tears or saliva

(c) Ionic and polar regions on the protein's surface attract water molecules.

▲ **Figure 3.8 A water-soluble protein.** This figure shows human lysozyme, a protein found in tears and saliva that has antibacterial action.

regions of the water molecules are negatively charged and cling to sodium cations. The hydrogen regions are positively charged and are attracted to chloride anions. As a result, water molecules surround the individual sodium and chloride ions, separating and shielding them from one another. The sphere of water molecules around each dissolved ion is called a **hydration shell**. Working inward from the surface of each salt crystal, water eventually dissolves all the ions. The result is a solution of two solutes, sodium cations and chloride anions, homogeneously mixed with water, the solvent. Other ionic compounds also dissolve in water. Seawater, for instance, contains a great variety of dissolved ions, as do living cells.

A compound does not need to be ionic to dissolve in water; many compounds made up of nonionic polar molecules, such as sugars, are also water-soluble. Such compounds dissolve when water molecules surround each of the solute molecules, forming hydrogen bonds with them. Even molecules as large as proteins can dissolve in water if they have ionic and polar regions on their surface (**Figure 3.8**). Many different kinds of polar compounds are dissolved (along with ions) in the water of such biological fluids as blood, the sap of plants, and the liquid within all cells. Water is the solvent of life.

Hydrophilic and Hydrophobic Substances

Any substance that has an affinity for water is said to be **hydrophilic** (from the Greek *hydro*, water, and *philios*, loving). In some cases, substances can be hydrophilic without actually dissolving. For example, some molecules in cells are so large that they do not dissolve. Instead, they remain suspended in the aqueous liquid of the cell. Such a mixture is an example of a **colloid**, a stable suspension of fine particles in a liquid. Another example of a hydrophilic substance that does not dissolve is cotton, a plant product. Cotton consists of giant molecules of cellulose, a compound with numerous regions of partial positive and partial negative charges that can form hydrogen bonds with water. Water adheres to the cellulose fibers. Thus, a cotton towel does a great job of drying the body, yet does not dissolve in the washing machine. Cellulose is also present in the walls of water-conducting cells in a plant; you read earlier how the adhesion of water to these hydrophilic walls allows water transport to occur.

There are, of course, substances that do not have an affinity for water. Substances that are nonionic and nonpolar (or for some other reason cannot form hydrogen bonds) actually seem to repel water; these substances are said to be **hydrophobic** (from the Greek *phobos*, fearing). An example from the kitchen is vegetable oil, which, as you know, does not mix stably with water-based substances such as vinegar. The hydrophobic behavior of the oil molecules results from a prevalence of relatively nonpolar bonds, in this case bonds between carbon and hydrogen, which share electrons almost equally. Hydrophobic molecules related to oils are major ingredients of cell membranes. (Imagine what would happen to a cell if its membrane dissolved!)

Solute Concentration in Aqueous Solutions

Biological chemistry is "wet" chemistry. Most of the chemical reactions in organisms involve solutes dissolved in water. To understand such reactions, we must know how many atoms and molecules are involved and be able to calculate the concentration of solutes in an aqueous solution (the number of solute molecules in a volume of solution).

When carrying out experiments, we use mass to calculate the number of molecules. We know the mass of each atom in a given molecule, so we can calculate its **molecular mass**, which is simply the sum of the masses of all the atoms in a molecule. As an example, let's calculate the molecular mass of table sugar (sucrose), which has the molecular formula

$C_{12}H_{22}O_{11}$. In round numbers of daltons, the mass of a carbon atom is 12, the mass of a hydrogen atom is 1, and the mass of an oxygen atom is 16. Thus, sucrose has a molecular mass of 342 daltons. Of course, weighing out small numbers of molecules is not practical. For this reason, we usually measure substances in units called moles. Just as a dozen always means 12 objects, a **mole (mol)** represents an exact number of objects—6.02×10^{23}, which is called Avogadro's number. Because of the way in which Avogadro's number and the unit *dalton* were originally defined, there are 6.02×10^{23} daltons in 1 g. This is significant because once we determine the molecular mass of a molecule such as sucrose, we can use the same number (342), but with the unit *gram*, to represent the mass of 6.02×10^{23} molecules of sucrose, or 1 mol of sucrose (this is sometimes called the *molar mass*). To obtain 1 mol of sucrose in the lab, therefore, we weigh out 342 g.

The practical advantage of measuring a quantity of chemicals in moles is that a mole of one substance has exactly the same number of molecules as a mole of any other substance. If the molecular mass of substance A is 342 daltons and that of substance B is 10 daltons, then 342 g of A will have the same number of molecules as 10 g of B. A mole of ethyl alcohol (C_2H_6O) also contains 6.02×10^{23} molecules, but its mass is only 46 g because the mass of a molecule of ethyl alcohol is less than that of a molecule of sucrose. Measuring in moles makes it convenient for scientists working in the laboratory to combine substances in fixed ratios of molecules.

How would we make a liter (L) of solution consisting of 1 mol of sucrose dissolved in water? We would measure out 342 g of sucrose and then gradually add water, while stirring, until the sugar was completely dissolved. We would then add enough water to bring the total volume of the solution up to 1 L. At that point, we would have a 1-molar (1 *M*) solution of sucrose. **Molarity**—the number of moles of solute per liter of solution—is the unit of concentration most often used by biologists for aqueous solutions.

CONCEPT CHECK 3.2

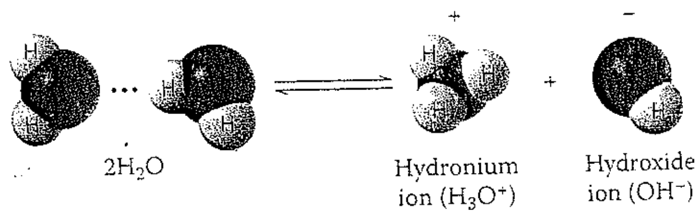
1. Describe how properties of water contribute to the upward movement of water in a tree.
2. Explain the saying "It's not the heat; it's the humidity."
3. How can the freezing of water crack boulders?
4. If you were a pharmacist, how would you make a 0.5-molar (0.5 *M*) solution of sodium chloride (NaCl)? (The atomic mass of Na is 23 daltons and that of Cl is 35.5 daltons.)
5. **WHAT IF?** A water strider's legs (see Figure 3.4) are coated with a hydrophobic substance. What might be the benefit? What would happen if the substance were hydrophilic?

For suggested answers, see Appendix A.

CONCEPT 3.3

Acidic and basic conditions affect living organisms

Occasionally, a hydrogen atom participating in a hydrogen bond between two water molecules shifts from one molecule to the other. When this happens, the hydrogen atom leaves its electron behind, and what is actually transferred is a **hydrogen ion** (H^+), a single proton with a charge of 1+. The water molecule that lost a proton is now a **hydroxide ion** (OH^-), which has a charge of 1–. The proton binds to the other water molecule, making that molecule a **hydronium ion** (H_3O^+). We can picture the chemical reaction this way:



By convention, H^+ (the hydrogen ion) is used to represent H_3O^+ (the hydronium ion), and we follow that practice here. Keep in mind, though, that H^+ does not exist on its own in an aqueous solution. It is always associated with another water molecule in the form of H_3O^+.

As indicated by the double arrows, this is a reversible reaction that reaches a state of dynamic equilibrium when water molecules dissociate at the same rate that they are being re-formed from H^+ and OH^-. At this equilibrium point, the concentration of water molecules greatly exceeds the concentrations of H^+ and OH^-. In pure water, only one water molecule in every 554 million is dissociated. The concentration of each ion in pure water is 10^{-7} *M* (at 25°C). This means there is only one ten-millionth of a mole of hydrogen ions per liter of pure water and an equal number of hydroxide ions.

Although the dissociation of water is reversible and statistically rare, it is exceedingly important in the chemistry of life. H^+ and OH^- are very reactive. Changes in their concentrations can drastically affect a cell's proteins and other complex molecules. As we have seen, the concentrations of H^+ and OH^- are equal in pure water, but adding certain kinds of solutes, called acids and bases, disrupts this balance. Biologists use something called the pH scale to describe how acidic or basic (the opposite of acidic) a solution is. In the remainder of this chapter, you will learn about acids, bases, and pH and why changes in pH can adversely affect organisms.

Effects of Changes in pH

Before discussing the pH scale, let's see what acids and bases are and how they interact with water.

Acids and Bases

What would cause an aqueous solution to have an imbalance in H^+ and OH^- concentrations? When acids dissolve in water, they donate additional H^+ to the solution. An **acid** is a substance that increases the hydrogen ion concentration of a solution. For example, when hydrochloric acid (HCl) is added to water, hydrogen ions dissociate from chloride ions:

$$HCl \longrightarrow H^+ + Cl^-$$

This source of H^+ (dissociation of water is the other source) results in an acidic solution—one having more H^+ than OH^-.

A substance that reduces the hydrogen ion concentration of a solution is called a **base**. Some bases reduce the H^+ concentration directly by accepting hydrogen ions. Ammonia (NH_3), for instance, acts as a base when the unshared electron pair in nitrogen's valence shell attracts a hydrogen ion from the solution, resulting in an ammonium ion (NH_4^+):

$$NH_3 + H^+ \rightleftharpoons NH_4^+$$

Other bases reduce the H^+ concentration indirectly by dissociating to form hydroxide ions, which combine with hydrogen ions and form water. One such base is sodium hydroxide (NaOH), which in water dissociates into its ions:

$$NaOH \longrightarrow Na^+ + OH^-$$

In either case, the base reduces the H^+ concentration. Solutions with a higher concentration of OH^- than H^+ are known as basic solutions. A solution in which the H^+ and OH^- concentrations are equal is said to be neutral.

Notice that single arrows were used in the reactions for HCl and NaOH. These compounds dissociate completely when mixed with water, and so hydrochloric acid is called a strong acid and sodium hydroxide a strong base. In contrast, ammonia is a relatively weak base. The double arrows in the reaction for ammonia indicate that the binding and release of hydrogen ions are reversible reactions, although at equilibrium there will be a fixed ratio of NH_4^+ to NH_3.

There are also weak acids, which reversibly release and accept back hydrogen ions. An example is carbonic acid:

$$\underset{\text{Carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{Bicarbonate ion}}{HCO_3^-} + \underset{\text{Hydrogen ion}}{H^+}$$

Here the equilibrium so favors the reaction in the left direction that when carbonic acid is added to water, only 1% of the molecules are dissociated at any particular time. Still, that is enough to shift the balance of H^+ and OH^- from neutrality.

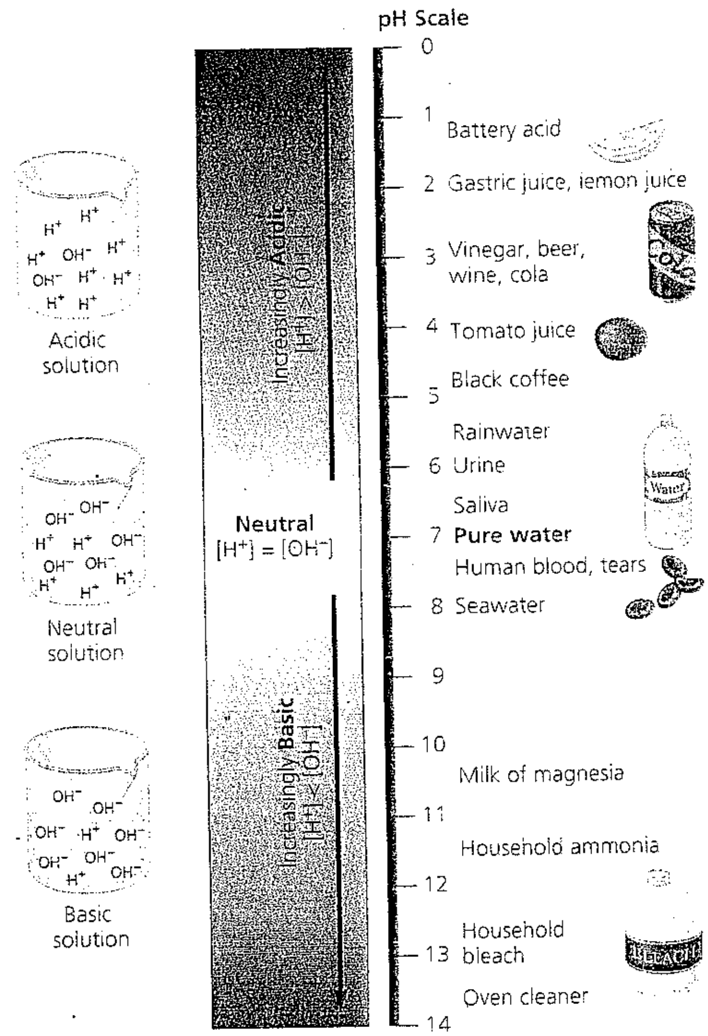
The pH Scale

In any aqueous solution at 25°C, the *product* of the H^+ and OH^- concentrations is constant at 10^{-14}. This can be written

$$[H^+][OH^-] = 10^{-14}$$

In such an equation, brackets indicate molar concentration. In a neutral solution at room temperature (25°C), $[H^+] = 10^{-7}$ and $[OH^-] = 10^{-7}$, so in this case, 10^{-14} is the product of $10^{-7} \times 10^{-7}$. If enough acid is added to a solution to increase $[H^+]$ to 10^{-5} *M*, then $[OH^-]$ will decline by an equivalent amount to 10^{-9} *M* (note that $10^{-5} \times 10^{-9} = 10^{-14}$). This constant relationship expresses the behavior of acids and bases in an aqueous solution. An acid not only adds hydrogen ions to a solution, but also removes hydroxide ions because of the tendency for H^+ to combine with OH^-, forming water. A base has the opposite effect, increasing OH^- concentration but also reducing H^+ concentration by the formation of water. If enough of a base is added to raise the OH^- concentration to 10^{-4} *M*, it will cause the H^+ concentration to drop to 10^{-10} *M*. Whenever we know the concentration of either H^+ or OH^- in an aqueous solution, we can deduce the concentration of the other ion.

Because the H^+ and OH^- concentrations of solutions can vary by a factor of 100 trillion or more, scientists have developed a way to express this variation more conveniently than in moles per liter. The pH scale (**Figure 3.9**) compresses the



▲ **Figure 3.9 The pH scale and pH values of some aqueous solutions.**

range of H^+ and OH^- concentrations by employing logarithms. The **pH** of a solution is defined as the negative logarithm (base 10) of the hydrogen ion concentration:

$$pH = -\log [H^+]$$

For a neutral aqueous solution, $[H^+]$ is 10^{-7} *M*, giving us

$$-\log 10^{-7} = -(-7) = 7$$

Notice that pH *declines* as H^+ concentration *increases*. Notice, too, that although the pH scale is based on H^+ concentration, it also implies OH^- concentration. A solution of pH 10 has a hydrogen ion concentration of 10^{-10} *M* and a hydroxide ion concentration of 10^{-4} *M*.

The pH of a neutral aqueous solution at 25°C is 7, the midpoint of the scale. A pH value less than 7 denotes an acidic solution; the lower the number, the more acidic the solution. The pH for basic solutions is above 7. Most biological fluids are within the range pH 6–8. There are a few exceptions, however, including the strongly acidic digestive juice of the human stomach, which has a pH of about 2.

Remember that each pH unit represents a tenfold difference in H^+ and OH^- concentrations. It is this mathematical feature that makes the pH scale so compact. A solution of pH 3 is not twice as acidic as a solution of pH 6, but a thousand times more acidic. When the pH of a solution changes slightly, the actual concentrations of H^+ and OH^- in the solution change substantially.

Buffers

The internal pH of most living cells is close to 7. Even a slight change in pH can be harmful, because the chemical processes of the cell are very sensitive to the concentrations of hydrogen and hydroxide ions.

The pH of human blood is very close to 7.4, which is slightly basic. A person cannot survive for more than a few minutes if the blood pH drops to 7 or rises to 7.8, and a chemical system exists in the blood that maintains a stable pH. If you add 0.01 mol of a strong acid to a liter of pure water, the pH drops from 7.0 to 2.0. If the same amount of acid is added to a liter of blood, however, the pH decrease is only from 7.4 to 7.3. Why does the addition of acid have so much less of an effect on the pH of blood than it does on the pH of water? The presence of substances called buffers allows for a relatively constant pH in biological fluids despite the addition of acids or bases. **Buffers** are substances that minimize changes in the concentrations of H^+ and OH^- in a solution. They do so by accepting hydrogen ions from the solution when they are in excess and donating hydrogen ions to the solution when they have been depleted. Most buffer solutions contain a weak acid and its corresponding base, which combine reversibly with hydrogen ions. There are several buffers that contribute to pH stability in human blood and many other biological solutions. One of these is carbonic acid (H_2CO_3), formed when CO_2 reacts with water in blood plasma. As mentioned earlier, carbonic acid dissociates to yield a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+):

$$\underset{\substack{H^+\text{ donor}\\(\text{acid})}}{H_2CO_3} \underset{\text{Response to a drop in pH}}{\overset{\text{Response to a rise in pH}}{\rightleftharpoons}} \underset{\substack{H^+\text{ acceptor}\\(\text{base})}}{HCO_3^-} + \underset{\substack{\text{Hydrogen}\\\text{ion}}}{H^+}$$

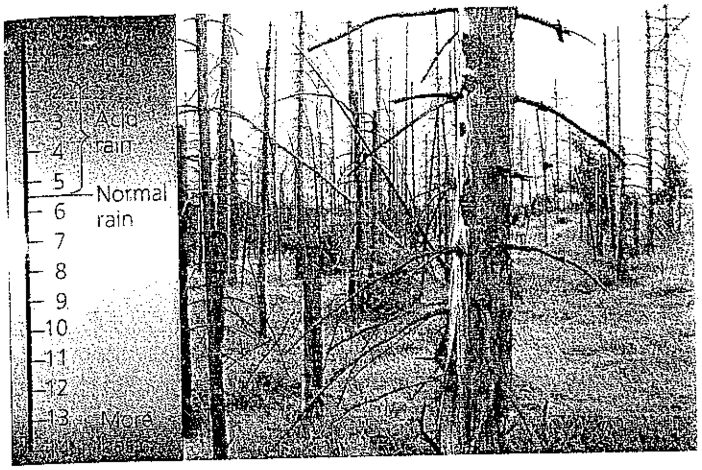
The chemical equilibrium between carbonic acid and bicarbonate acts as a pH regulator, the reaction shifting left or right as other processes in the solution add or remove hydrogen ions. If the H^+ concentration in blood begins to fall (that is, if pH rises), the reaction proceeds to the right and more carbonic acid dissociates, replenishing hydrogen ions. But when H^+ concentration in blood begins to rise (when pH drops), the reaction proceeds to the left, with HCO_3^- (the base) removing the hydrogen ions from the solution and forming H_2CO_3. Thus, the carbonic acid–bicarbonate buffering system consists of an acid and a base in equilibrium with each other. Most other buffers are also acid-base pairs.

Threats to Water Quality on Earth

Considering the dependence of all life on water, contamination of rivers, lakes, seas, and rain is a dire environmental problem. Many threats to water quality have been posed by human activities. Consider, for example, the burning of fossil fuels (coal, oil, and gas). This practice, which has been increasing since the Industrial Revolution in the 1800s, releases gaseous compounds into the atmosphere, including prodigious amounts of CO_2. The chemical reactions of these compounds with water alter the delicate balance of conditions for life on Earth by affecting water pH and temperature.

The burning of fossil fuels is a major source of sulfur oxides and nitrous oxides. These react with water in the air to form strong acids, which fall to Earth with rain or snow. **Acid precipitation** refers to rain, snow, or fog with a pH lower (more acidic) than pH 5.2. (Uncontaminated rain has a pH of about 5.6, slightly acidic, owing to the formation of carbonic acid from carbon dioxide and water.) Electric power plants that burn coal produce more of these oxides than any other single source. Winds carry the pollutants away, and acid rain may fall hundreds of kilometers away from industrial centers. In certain sites in Pennsylvania and New York, the pH of rainfall in December 2001 averaged 4.3, about 20 times more acidic than normal rain. Acid precipitation falls on many other regions, including eastern Canada, the Cascade Mountains of the Pacific Northwest, and certain parts of Europe and Asia (**Figure 3.10**).

Acid precipitation can damage life in lakes and streams. Also, acid precipitation falling on land adversely affects soil chemistry and has taken a toll on some North American and European forests (see Figure 3.10). Nevertheless, studies indicate that the majority of North American forests are not



▲ **Figure 3.10 Acid precipitation and its effects on a forest.** Acid rain is thought to be responsible for killing trees in many forests, including the fir forest shown here in the Czech Republic.

currently suffering substantially from acid precipitation, in large part due to amendments made in 1990 to the Clean Air Act.

Carbon dioxide, the main product of fossil fuel combustion, causes other problems. Its release into the atmosphere has been increasing steadily and is expected to double by the year 2065, relative to 1880 levels. About half of the CO_2 stays in the atmosphere, acting like a reflective blanket over the planet that prevents heat from radiating into outer space. This "greenhouse" effect and the problems associated with it will be discussed in Chapter 55. A portion of the CO_2 is taken up by trees and other organisms during photosynthesis, as mentioned in Chapter 2. The remainder—about 30% or so—is absorbed by the oceans. In spite of the huge volume of water in the oceans, scientists worry that this absorption of so much CO_2 will harm marine life and ecosystems.

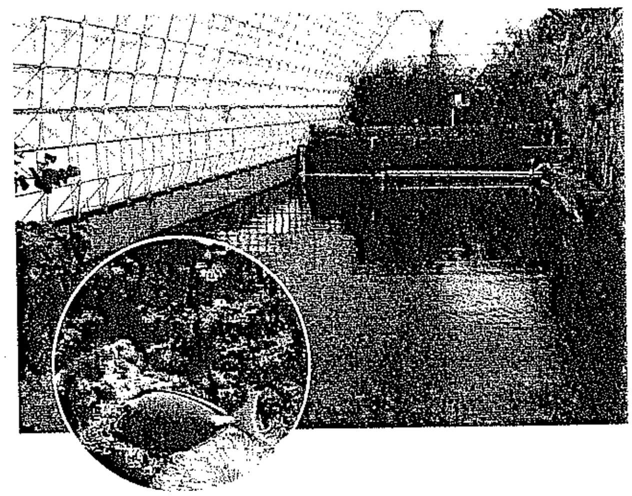
When CO_2 dissolves in seawater, it reacts with water (H_2O) to form carbonic acid (H_2CO_3). Almost all of the carbonic acid in turn dissociates, producing protons and a balance between two ions, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). As seawater acidifies due to the extra protons, the balance shifts toward HCO_3^-, lowering the concentration of CO_3^{2-}. Many studies have shown that calcification, the production of calcium carbonate ($CaCO_3$) by corals and other organisms, is directly affected by the concentration of CO_3^{2-}. Any decrease in CO_3^{2-} is therefore of great concern because calcification accounts for the formation of coral reefs in our tropical seas. These sensitive ecosystems act as havens for a great diversity of organisms.

Perhaps one of the best-known and longest studies on coral reef calcification was carried out by scientists at the ecosystem center in Arizona known as Biosphere-2. The center includes an artificial coral reef system in which the temperature and chemistry of the seawater can be controlled and manipulated. Chris Langdon and colleagues used this system to test the effects of varying the concentration of CO_3^{2-} on the rate of calcification in the coral reef (**Figure 3.11**). Together with

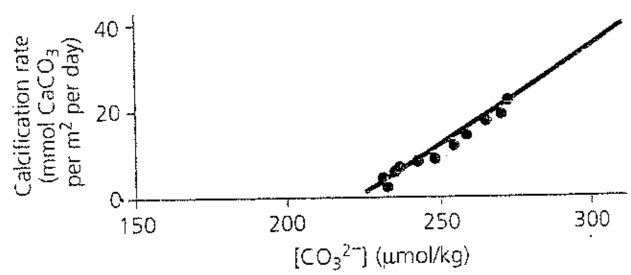
▼ **Figure 3.11 Inquiry**

What is the effect of carbonate ion concentration on coral reef calcification?

EXPERIMENT Chris Langdon and colleagues at Columbia University wondered how the increase in CO_2 emissions due to burning of fossil fuels and the resulting decrease in CO_3^{2-} concentration in the oceans affect coral reefs. They took advantage of the artificial coral reef system at Biosphere-2. This 2,650-cubic-meter (m^3) aquarium behaves like a natural coral reef community. For almost four years, these researchers varied the carbonate concentration in the seawater under controlled conditions and measured the rate of calcification by reef organisms.



RESULTS The calcification rate was observed to be lower at lower concentrations of carbonate ion ($[CO_3^{2-}]$).



CONCLUSION Coral reefs could be endangered by reduced $[CO_3^{2-}]$. Other studies have predicted a doubling of CO_2 emissions from 1880 to 2065 and a resulting decrease in carbonate ion concentration. Combining those predictions with the results of this study, the authors predict that by 2065 the rate of coral reef calcification may decrease by 40% relative to preindustrial levels.

SOURCE C. Langdon et al., Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef, *Global Biogeochemical Cycles* 14:639–654 (2000).

WHAT IF? The data above were for a particular concentration of calcium (Ca^{2+}). The series of experiments included measurements at two higher concentrations of Ca^{2+}. Given that the following reaction represents calcification, predict how the $[Ca^{2+}]$ would affect the results and explain why.

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3$$

conclusions from other studies, their results led them to predict that the expected doubling of CO_2 emissions by the year 2065 could lead to a 40% decrease in coral reef calcification. Although scientists may not agree on the exact percentage, most concur that this and other studies provide cause for grave concern.

If there is reason for optimism about the future quality of water resources on our planet, it is that we have made progress in learning about the delicate chemical balances in oceans and other bodies of water. Continued progress can come only from the actions of people who are concerned about environmental quality. This requires understanding the crucial role that water plays in the environment's fitness for continued life on Earth.

CONCEPT CHECK 3.3

1. Compared with a basic solution at pH 9, the same volume of an acidic solution at pH 4 has ___ times as many hydrogen ions (H^+).
2. HCl is a strong acid that dissociates in water: $HCl \longrightarrow H^+ + Cl^-$. What is the pH of 0.01 *M* HCl?
3. Acetic acid (CH_3COOH) can be a buffer, similar to carbonic acid. Write the dissociation reaction, identifying the acid, base, H^+ acceptor, and H^+ donor.
4. **WHAT IF?** Given a liter of pure water and a liter solution of acetic acid, what would happen to the pH if you added 0.01 mol of a strong acid to each? Use the reaction equation to explain the result.

For suggested answers, see Appendix A.

Chapter 3 Review

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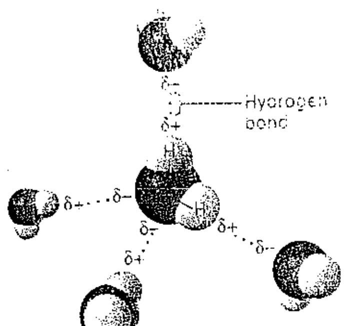
SUMMARY OF KEY CONCEPTS

CONCEPT 3.1

The polarity of water molecules results in hydrogen bonding (pp. 46–47)

- A hydrogen bond forms when the slightly negatively charged oxygen of one water molecule is attracted to the slightly positively charged hydrogen of a nearby molecule. Hydrogen bonding between water molecules is the basis for water's unusual properties.



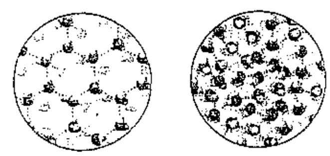
MEDIA

Activity The Polarity of Water

CONCEPT 3.2

Four emergent properties of water contribute to Earth's fitness for life (pp. 47–52)

- **Cohesion** Hydrogen bonding keeps water molecules close to each other, and this cohesion helps pull water upward in the microscopic water-conducting cells of plants. Hydrogen bonding is also responsible for water's surface tension.
- **Moderation of Temperature** Water has a high specific heat: Heat is absorbed when hydrogen bonds break and is released when hydrogen bonds form. This helps keep temperatures relatively steady, within limits that permit life. Evaporative cooling is based on water's high heat of vaporization. The evaporative loss of the most energetic water molecules cools a surface.
- **Insulation of Bodies of Water by Floating Ice** Ice floats because it is less dense than liquid water. This allows life to exist under the frozen surfaces of lakes and polar seas.



Ice: stable hydrogen bonds — **Liquid water:** transient hydrogen bonds

- **The Solvent of Life** Water is an unusually versatile solvent because its polar molecules are attracted to charged and polar substances capable of forming hydrogen bonds. Hydrophilic substances have an affinity for water; hydrophobic substances do not. Molarity, the number of moles of solute per liter of solution, is used as a measure of solute concentration in solutions. A mole is a certain number of molecules of a substance. The mass of a mole of the substance in grams is the same as the molecular mass in daltons.

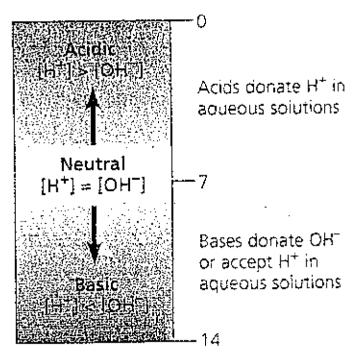
MEDIA

MP3 Tutor The Properties of Water
Activity Cohesion of Water

CONCEPT 3.3

Acidic and basic conditions affect living organisms (pp. 52–56)

- A water molecule can transfer an H^+ to another water molecule to form H_3O^+ (represented simply by H^+) and OH^-.
- **Effects of Changes in pH** The concentration of H^+ is expressed as pH, where $pH = -\log [H^+]$. Buffers in biological fluids resist changes in pH. A buffer consists of an acid-base pair that combines reversibly with hydrogen ions.



- **Threats to Water Quality on Earth** The burning of fossil fuels results in emission of oxides (leading to acid precipitation) and increasing amounts of CO_2. Some CO_2 becomes dissolved in the oceans, lowering pH and potentially affecting the rate of calcification on coral reefs.

MEDIA

Activity Dissociation of Water Molecules
Activity Acids, Bases, and pH
Investigation How Does Acid Precipitation Affect Trees?

TESTING YOUR KNOWLEDGE

SELF-QUIZ

1. Many mammals control their body temperature by sweating. Which property of water is most directly responsible for the ability of sweat to lower body temperature?
   a. water's change in density when it condenses
   b. water's ability to dissolve molecules in the air
   c. the release of heat by the formation of hydrogen bonds
   d. the absorption of heat by the breaking of hydrogen bonds
   e. water's high surface tension

2. A slice of pizza has 500 kcal. If we could burn the pizza and use all the heat to warm a 50-L container of cold water, what would be the approximate increase in the temperature of the water? (*Note:* A liter of cold water weighs about 1 kg.)
   a. 50°C
   b. 5°C
   c. 10°C
   d. 100°C
   e. 1°C

3. The bonds that are broken when water vaporizes are
   a. ionic bonds.
   b. hydrogen bonds between water molecules.
   c. covalent bonds between atoms within water molecules.
   d. polar covalent bonds.
   e. nonpolar covalent bonds.

4. Which of the following is a hydrophobic material?
   a. paper
   b. table salt
   c. wax
   d. sugar
   e. pasta

5. We can be sure that a mole of table sugar and a mole of vitamin C are equal in their
   a. mass in daltons.
   b. mass in grams.
   c. number of molecules.
   d. number of atoms.
   e. volume.

6. How many grams of acetic acid ($C_2H_4O_2$) would you use to make 10 L of a 0.1 *M* aqueous solution of acetic acid? (*Note:* The atomic masses, in daltons, are approximately 12 for carbon, 1 for hydrogen, and 16 for oxygen.)
   a. 10.0 g
   b. 0.1 g
   c. 6.0 g
   d. 60.0 g
   e. 0.6 g

7. Measurements show that the pH of a particular lake is 4.0. What is the hydrogen ion concentration of the lake?
   a. 4.0 *M*
   b. 10^{-10} *M*
   c. 10^{-4} *M*
   d. 10^{4} *M*
   e. 4%

8. What is the *hydroxide* ion concentration of the lake described in question 7?
   a. 10^{-7} *M*
   b. 10^{-4} *M*
   c. 10^{-10} *M*
   d. 10^{-14} *M*
   e. 10 *M*

9. **DRAW IT** Draw three water molecules, using space-filling models, and label the atoms. Draw solid lines to indicate covalent bonds and dotted lines for hydrogen bonds. Add partial-charge labels as appropriate.

For Self-Quiz answers, see Appendix A.

MEDIA Visit the Study Area at **www.masteringbio.com** for a Practice Test.

EVOLUTION CONNECTION

10. The surface of the planet Mars has many landscape features reminiscent of those formed by flowing water on Earth, including what appear to be meandering channels and outwash areas. In 2004, images of Meridiani Planum on Mars taken by NASA's *Opportunity* rover suggested that liquid water was once present on its surface. For example, one image (left, above) shows polygonal fractures in the rock. Similar fracture patterns in rocks on Earth's surface (above, right) correlate with the earlier presence of water. Ice exists at the Martian poles today, and some scientists suspect a great deal more water may be present beneath the Martian surface. Why has there been so much interest in the presence of water on Mars? Does the presence of water make it more likely that life arose there? What other physical factors might also be important?

Surface of Mars

Surface of Earth

SCIENTIFIC INQUIRY

11. Design a controlled experiment to test the hypothesis that acid precipitation inhibits the growth of *Elodea*, a common freshwater plant (see Figure 2.19).

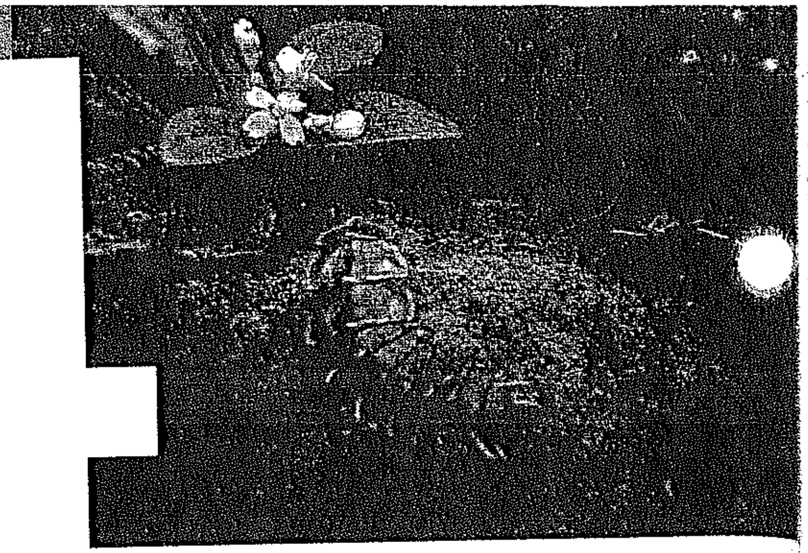
12. In agricultural areas, farmers pay close attention to the weather forecast. Right before a predicted overnight freeze, farmers spray water on crops to protect the plants. Use the properties of water to explain how this method works. Be sure to mention why hydrogen bonds are responsible for this phenomenon.

SCIENCE, TECHNOLOGY, AND SOCIETY

13. Agriculture, industry, and the growing populations of cities all compete, through political influence, for water. If you were in charge of water resources in an arid region, what would your priorities be for allocating the limited water supply for various uses? How would you try to build consensus among the different special-interest groups?

Carbon and the Molecular Diversity of Life

4



▲ **Figure 4.1 What properties of carbon underlie its role as the molecular basis of life?**

KEY CONCEPTS

4.1 Organic chemistry is the study of carbon compounds
4.2 Carbon atoms can form diverse molecules by bonding to four other atoms
4.3 A small number of chemical groups are key to the functioning of biological molecules

OVERVIEW

Carbon: The Backbone of Life

Although water is the universal medium for life on Earth, living organisms, such as the plants and trilobite beetle in **Figure 4.1**, are made up of chemicals that are based mostly on the element carbon. Carbon enters the biosphere through the action of plants, which use solar energy to transform atmospheric CO_2 into the molecules of life. These molecules are passed along to animals that feed on plants.

Of all chemical elements, carbon is unparalleled in its ability to form molecules that are large, complex, and diverse, and this molecular diversity has made possible the diversity of organisms that have evolved on Earth. Proteins, DNA, carbohydrates, and other molecules that distinguish living matter from inanimate material are all composed of carbon atoms bonded to one another and to atoms of other elements. Hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and phosphorus (P) are other common ingredients of these compounds, but it is the element carbon (C) that accounts for the large diversity of biological molecules.

Proteins and other very large molecules are the main focus of Chapter 5. Here we investigate the properties of smaller molecules. We will use these molecules to illustrate concepts of molecular architecture that will help explain why carbon is so important to life, at the same time highlighting the theme that emergent properties arise from the organization of matter in living organisms.

CONCEPT 4.1

Organic chemistry is the study of carbon compounds

For historical reasons, compounds containing carbon are said to be organic, and the branch of chemistry that specializes in the study of carbon compounds is called **organic chemistry**. Organic compounds range from simple molecules, such as methane (CH_4), to colossal ones, such as proteins, with thousands of atoms. Most organic compounds contain hydrogen atoms in addition to carbon atoms.

The overall percentages of the major elements of life—C, H, O, N, S, and P—are quite uniform from one organism to another. Because of carbon's versatility, however, this limited assortment of atomic building blocks, taken in roughly the same proportions, can be used to build an inexhaustible variety of organic molecules. Different species of organisms, and different individuals within a species, are distinguished by variations in their organic molecules.

Since the dawn of human history, people have used other organisms as sources of valued substances—from foods and medicines to fabrics. The science of organic chemistry originated in attempts to purify and improve the yield of such products. By the early 1800s, chemists had learned to make many simple compounds in the laboratory by combining elements under the right conditions. Artificial synthesis of the complex molecules extracted from living matter seemed impossible, however. At that time, the Swedish chemist Jöns Jakob Berzelius made the distinction between organic compounds, those thought to arise only in living organisms, and inorganic compounds, those found only in the nonliving world. *Vitalism*, the belief in a life force outside the jurisdiction of physical and chemical laws, provided the foundation for the new discipline of organic chemistry.

Chemists began to chip away at the foundation of vitalism when they finally learned to synthesize organic compounds in laboratories. In 1828, Friedrich Wöhler, a German chemist who had studied with Berzelius, attempted to make an "inorganic" salt, ammonium cyanate, by mixing solutions of ammonium ions (NH_4^+) and cyanate ions (CNO^-). Wöhler was astonished to find that instead he had made urea, an organic compound present in the urine of animals. Wöhler challenged the vitalists when he wrote, "I must tell you that I can prepare urea without requiring a kidney or an animal, either man or dog." However, one of the ingredients used in the synthesis, the cyanate, had been extracted from animal blood, and the vitalists were not swayed by Wöhler's discovery. A few years later, however, Hermann Kolbe, a student of Wöhler's, made the organic compound acetic acid from inorganic substances that could be prepared directly from pure elements.

Vitalism crumbled completely after several decades of laboratory synthesis of some increasingly complex organic compounds. In 1953, Stanley Miller, a graduate student of Harold Urey at the University of Chicago, helped bring this abiotic (nonliving) synthesis of organic compounds into the context of evolution in a classic experiment described in **Figure 4.2**. Miller's experiment, testing whether complex organic molecules could arise spontaneously under conditions thought to have existed on the early Earth, stimulated interest and further research on the origin of organic compounds. Some scientists have questioned whether the gases Miller used as starting materials were really present in the primitive Earth's atmosphere. Recent work supports a slightly different recipe for early Earth's conditions; when used in the experiment, it led to the compounds Miller found. Although the jury is still out, these experiments support the idea that abiotic synthesis of organic compounds could have been an early stage in the origin of life.

The pioneers of organic chemistry helped shift the mainstream of biological thought from vitalism to *mechanism*, the view that physical and chemical laws govern all natural phenomena, including the processes of life. Organic chemistry was redefined as the study of carbon compounds, regardless of origin. Organisms produce most of the naturally occurring organic compounds, and these molecules represent a diversity and range of complexity unrivaled by inorganic compounds. However, the rules of chemistry apply to all molecules. The foundation of organic chemistry is not some intangible life force, but the unique chemical versatility of the element carbon.

CONCEPT CHECK 4.1

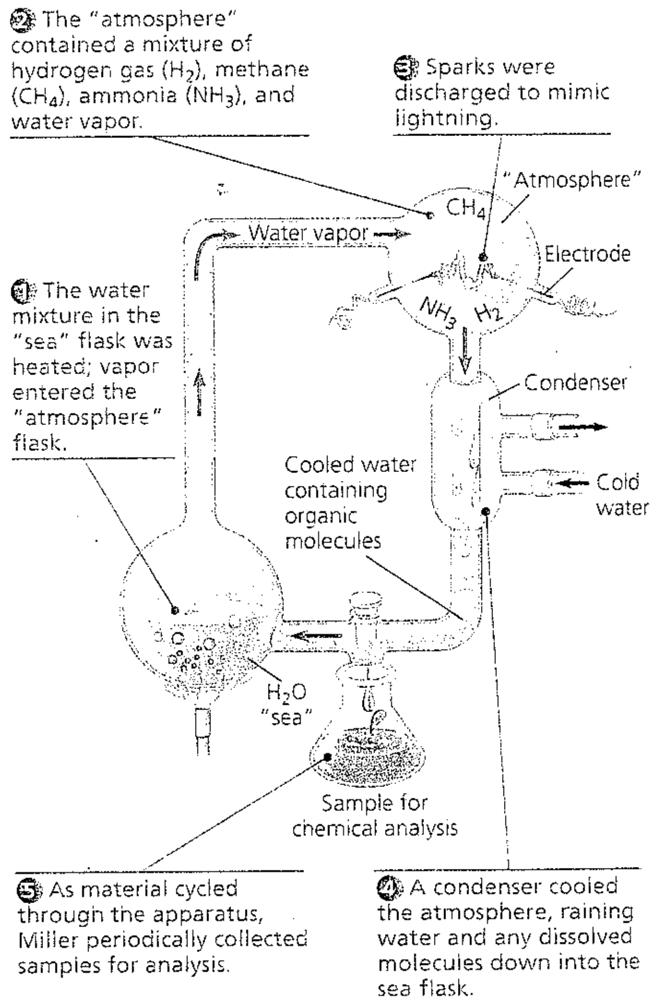
1. What conclusion did Stanley Miller draw when he found amino acids in the products of his experiment?
2. WHAT IF? When Miller tried the experiment in Figure 4.2 without the electrical discharge, no organic compounds were found. What might explain this result?

For suggested answers, see Appendix A.

Figure 4.2 Inquiry

Can organic molecules form under conditions believed to simulate those on the early Earth?

EXPERIMENT In 1953, Stanley Miller set up a closed system to simulate conditions thought to have existed on the early Earth. A flask of water simulated the primeval sea. The water was heated so that some vaporized and moved into a second, higher flask containing the "atmosphere"—a mixture of gases. Sparks were discharged in the synthetic atmosphere to mimic lightning.



RESULTS Miller identified a variety of organic molecules that are common in organisms. These included simple compounds such as formaldehyde (CH_2O) and hydrogen cyanide (HCN) and more complex molecules such as amino acids and long chains of carbon and hydrogen known as hydrocarbons.

CONCLUSION Organic molecules, a first step in the origin of life, may have been synthesized abiotically on the early Earth. (We will explore this hypothesis in more detail in Chapter 25.)

SOURCE S. Miller, A production of amino acids under possible primitive Earth conditions, *Science* 117:528–529 (1953).

WHAT IF? If Miller had increased the concentration of NH_3 in his experiment, how might the relative amounts of the products HCN and CH_2O have differed?

CONCEPT 4.2

Carbon atoms can form diverse molecules by bonding to four other atoms

The key to an atom's chemical characteristics is its electron configuration. This configuration determines the kinds and number of bonds an atom will form with other atoms.

The Formation of Bonds with Carbon

Carbon has 6 electrons, with 2 in the first electron shell and 4 in the second shell. Having 4 valence electrons in a shell that holds 8, carbon would have to donate or accept 4 electrons to complete its valence shell and become an ion. Instead, a carbon atom usually completes its valence shell by sharing its 4 electrons with other atoms in covalent bonds so that 8 electrons are present. These bonds may include single and double covalent bonds. Each carbon atom thus acts as an intersection point from which a molecule can branch off in as many as four directions. This *tetravalence* is one facet of carbon's versatility that makes large, complex molecules possible.

When a carbon atom forms four single covalent bonds, the arrangement of its four hybrid orbitals causes the bonds to angle toward the corners of an imaginary tetrahedron (see Figure 2.17b). The bond angles in methane (CH_4) are 109.5° (**Figure 4.3a**), and they are roughly the same in any group of atoms where carbon has four single bonds. For example, ethane (C_2H_6) is shaped like two overlapping tetrahedrons (**Figure 4.3b**). In molecules with more carbons, every grouping of a carbon bonded to four other atoms has a tetrahedral shape. But when two carbon atoms are joined by a double bond, all bonds around those carbons are in the same plane. For example, ethene (C_2H_4) is a flat molecule; its atoms all lie in the same plane (**Figure 4.3c**). We find it convenient to write all structural formulas as though the molecules represented were flat, but keep in mind that molecules are three-dimensional and that the shape of a molecule often determines its function.

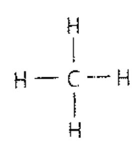
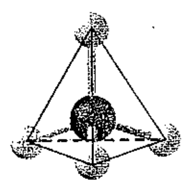
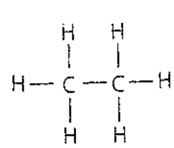
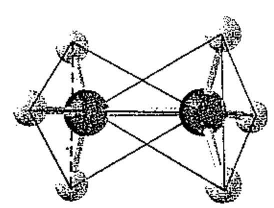
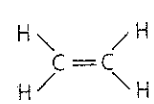
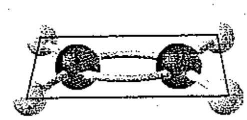
The electron configuration of carbon gives it covalent compatibility with many different elements. **Figure 4.4** shows the valences of carbon and its most frequent partners—oxygen, hydrogen, and nitrogen. These are the four major atomic components of organic molecules. These valences are the basis for the rules of covalent bonding in organic chemistry—the building code for the architecture of organic molecules.

Let's consider how the rules of covalent bonding apply to carbon atoms with partners other than hydrogen. We'll look at two examples, the simple molecules carbon dioxide and urea.

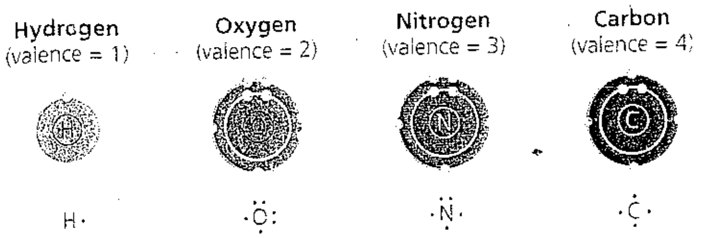
In the carbon dioxide molecule (CO_2), a single carbon atom is joined to two atoms of oxygen by double covalent bonds. The structural formula for CO_2 is shown here:

$$O{=}C{=}O$$

Each line in a structural formula represents a pair of shared electrons. The two double bonds formed by the carbon atom are the equivalent of four single covalent bonds. The arrangement completes the valence shells of all atoms in the molecule. Because CO_2 is a very simple molecule and lacks hydrogen, it is often considered inorganic, even though it contains carbon.

Name and Comment	Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
(a) Methane. When a carbon atom has four single bonds to other atoms, the molecule is tetrahedral.	CH_4			
(b) Ethane. A molecule may have more than one tetrahedral group of single-bonded atoms. (Ethane consists of two such groups.)	C_2H_6			
(c) Ethene (ethylene). When two carbon atoms are joined by a double bond, all atoms attached to those carbons are in the same plane; the molecule is flat.	C_2H_4			

▲ **Figure 4.3 The shapes of three simple organic molecules.**

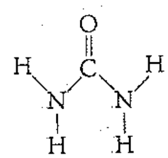


▲ **Figure 4.4 Valences of the major elements of organic molecules.** Valence is the number of covalent bonds an atom can form. It is generally equal to the number of electrons required to complete the valence (outermost) shell (see Figure 2.9). All the electrons are shown for each atom in the electron distribution diagrams (top). Only the electrons in the valence shell are presented in the Lewis dot structures.

DRAW IT *Refer to Figure 2.9 and draw the Lewis dot structures for sodium, phosphorus, sulfur, and chlorine.*

Whether we call CO_2 organic or inorganic, however, it is clearly important to the living world as the source of carbon for all organic molecules in organisms.

Urea, $CO(NH_2)_2$, is the organic compound found in urine that Wöhler synthesized in the early 1800s. The structural formula for urea is shown at the right. Again, each atom has the required number of covalent bonds. In this case, one carbon atom is involved in both single and double bonds.



Urea

Urea and carbon dioxide are molecules with one carbon atom. But as Figure 4.3 shows, a carbon atom can also use one or more valence electrons to form covalent bonds to other carbon atoms, linking the atoms into chains of seemingly infinite variety.

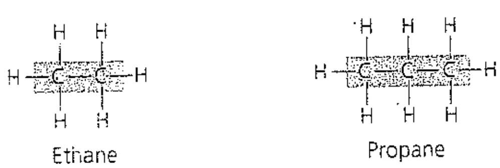
Molecular Diversity Arising from Carbon Skeleton Variation

Carbon chains form the skeletons of most organic molecules (**Figure 4.5**). The skeletons vary in length and may be straight, branched, or arranged in closed rings. Some carbon skeletons have double bonds, which vary in number and location. Such variation in carbon skeletons is one important source of the molecular complexity and diversity that characterize living matter. In addition, atoms of other elements can be bonded to the skeletons at available sites.

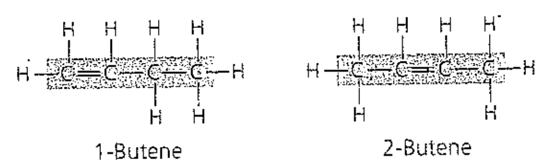
Hydrocarbons

All of the molecules that are shown in Figures 4.3 and 4.5 are **hydrocarbons**, organic molecules consisting of only carbon and hydrogen. Atoms of hydrogen are attached to the carbon skeleton wherever electrons are available for covalent bonding. Hydrocarbons are the major components of petroleum, which is called a fossil fuel because it consists of the partially decomposed remains of organisms that lived millions of years ago.

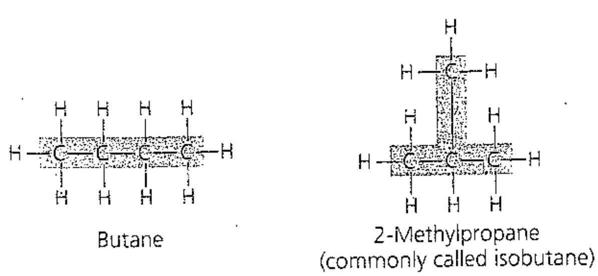
Although hydrocarbons are not prevalent in living organisms, many of a cell's organic molecules have regions consisting of only carbon and hydrogen. For example, the molecules known as fats have long hydrocarbon tails attached to a nonhydrocarbon component (**Figure 4.6**, on next page). Neither petroleum nor fat dissolves in water; both are hydrophobic compounds because the great majority of their bonds are relatively nonpolar carbon-to-hydrogen linkages. Another characteristic of hydrocarbons is that they can undergo reactions that release a relatively large amount of energy. The gasoline that fuels a car consists of hydrocarbons, and the hydrocarbon tails of fat molecules serve as stored fuel for animal bodies.



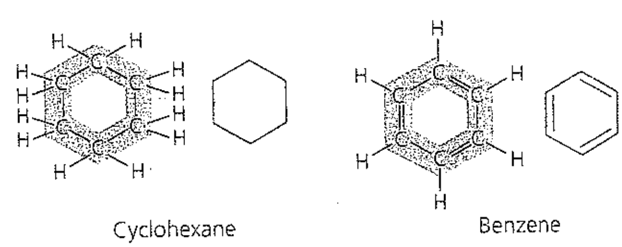
(a) Length. Carbon skeletons vary in length.



(c) Double bonds. The skeleton may have double bonds, which can vary in location.

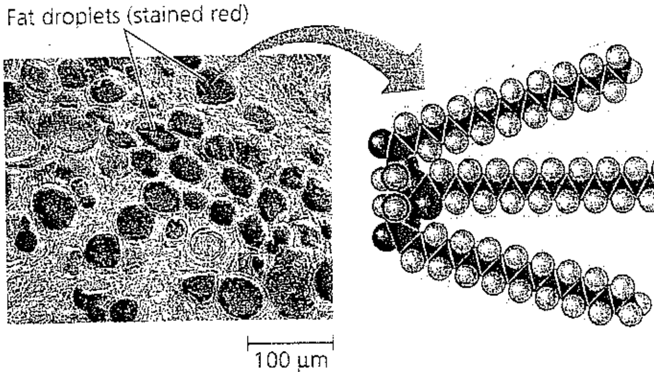


(b) Branching. Skeletons may be unbranched or branched.



(d) Rings. Some carbon skeletons are arranged in rings. In the abbreviated structural formula for each compound (at the right), each corner represents a carbon and its attached hydrogens.

▲ **Figure 4.5 Variations in carbon skeletons.** Hydrocarbons, organic molecules consisting only of carbon and hydrogen, illustrate the diversity of the carbon skeletons of organic molecules.



(a) Mammalian adipose cells **(b) A fat molecule**

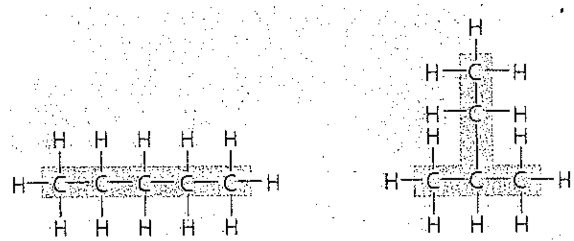
▲ **Figure 4.6 The role of hydrocarbons in fats. (a)** Mammalian adipose cells stockpile fat molecules as a fuel reserve. Each adipose cell in this micrograph is almost filled by a large fat droplet, which contains a huge number of fat molecules. **(b)** A fat molecule consists of a small, nonhydrocarbon component joined to three hydrocarbon tails. The tails can be broken down to provide energy. They also account for the hydrophobic behavior of fats. (Black = carbon; gray = hydrogen; red = oxygen.)

Isomers

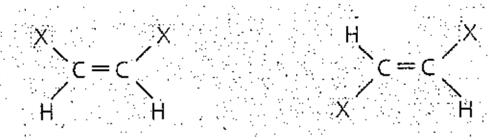
Variation in the architecture of organic molecules can be seen in **isomers,** compounds that have the same numbers of atoms of the same elements but different structures and hence different properties. Compare, for example, the two five-carbon compounds in **Figure 4.7a.** Both have the molecular formula C_5H_{12}, but they differ in the covalent arrangement of their carbon skeletons. The skeleton is straight in one compound but branched in the other. We will examine three types of isomers: structural isomers, geometric isomers, and enantiomers.

Structural isomers differ in the covalent arrangements of their atoms. The number of possible isomers increases tremendously as carbon skeletons increase in size. There are only 3 forms of C_5H_{12} (2 are shown in Figure 4.7a), but there are 18 variations of C_8H_{18} and 366,319 possible structural isomers of $C_{20}H_{42}$. Structural isomers may also differ in the location of double bonds.

Geometric isomers have the same covalent partnerships, but they differ in their spatial arrangements. The differences arise from the inflexibility of double bonds. Single bonds allow the atoms they join to rotate freely about the bond axis without changing the compound. In contrast, double bonds do not permit such rotation, resulting in the possibility of geometric isomers. If a double bond joins two carbon atoms, and each C also has two different atoms (or groups of atoms) attached to it, then two distinct geometric isomers are possible. Consider a simple molecule with two double-bonded carbons, each of which has an H and an X attached to it **(Figure 4.7b).** The arrangement with both Xs on the same side of the double bond is called a *cis* isomer, and the arrangement with the Xs on opposite sides is called a *trans* isomer. The subtle difference in shape between geometric isomers can dramatically affect the biological activities of organic molecules. For example, the biochemistry of vision involves a light-induced change of rhodopsin, a chemical compound in the eye, from the *cis* isomer to the *trans* isomer (see Chapter 50).



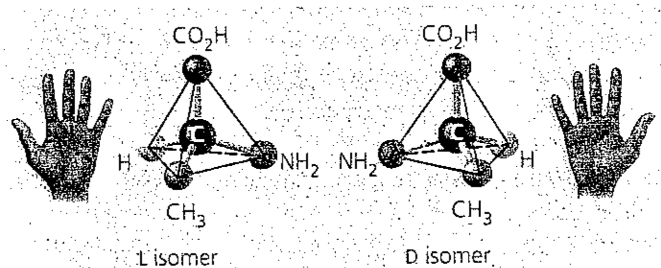
(a) Structural isomers differ in covalent partners, as shown in this example of two isomers of C_5H_{12}: pentane (left) and 2-methyl butane (right).



cis isomer: The two Xs are on the same side.

trans isomer: The two Xs are on opposite sides.

(b) Geometric isomers differ in arrangement about a double bond. In these diagrams, X represents an atom or group of atoms attached to a double-bonded carbon.



(c) Enantiomers differ in spatial arrangement around an asymmetric carbon, resulting in molecules that are mirror images, like left and right hands. The two isomers are designated the L and D isomers from the Latin for left and right (*levo* and *dextro*). Enantiomers cannot be superimposed on each other.

▲ **Figure 4.7 Three types of isomers.** Compounds with the same molecular formula but different structures, isomers are a source of diversity in organic molecules.

DRAW IT *There are three structural isomers of C_5H_{12}; draw the one not shown in (a).*

Enantiomers are isomers that are mirror images of each other. In the ball-and-stick models shown in **Figure 4.7c,** the middle carbon is called an *asymmetric carbon* because it is attached to four different atoms or groups of atoms. The four groups can be arranged in space around the asymmetric carbon in two different ways that are mirror images. Enantiomers are, in a way, left-handed and right-handed versions of the molecule. Just as your right hand won't fit into a left-handed glove, the working molecules in a cell can distinguish the two versions by shape. Usually, one isomer is biologically active, and the other is inactive.

The concept of enantiomers is important in the pharmaceutical industry because the two enantiomers of a drug may not be equally

Drug	Condition	Effective Enantiomer	Ineffective Enantiomer
Ibuprofen	Pain; inflammation	 S-Ibuprofen	 R-Ibuprofen
Albuterol	Asthma	 R-Albuterol	 S-Albuterol

▲ **Figure 4.8 The pharmacological importance of enantiomers.** Ibuprofen and albuterol are examples of drugs whose enantiomers have different effects. (*S* and *R* are letters used in one system to distinguish two enantiomers.) Ibuprofen reduces inflammation and pain. It is commonly sold as a mixture of the two enantiomers. The *S* enantiomer is 100 times more effective than the other. Albuterol is used to relax bronchial muscles, improving airflow in asthma patients. Only *R*-albuterol is synthesized and sold as a drug; the *S* form counteracts the active *R* form.

effective (**Figure 4.8**). In some cases, one of the isomers may even produce harmful effects. This was the case with thalidomide, a drug prescribed for thousands of pregnant women in the late 1950s and early 1960s. The drug was a mixture of two enantiomers. One enantiomer reduced morning sickness, the desired effect, but the other caused severe birth defects. (Unfortunately, even if the "good" thalidomide enantiomer is used in purified form, some of it soon converts to the "bad" enantiomer in the patient's body.) The differing effects of enantiomers in the body demonstrate that organisms are sensitive to even the most subtle variations in molecular architecture. Once again, we see that molecules have emergent properties that depend on the specific arrangement of their atoms.

CONCEPT CHECK 4.2

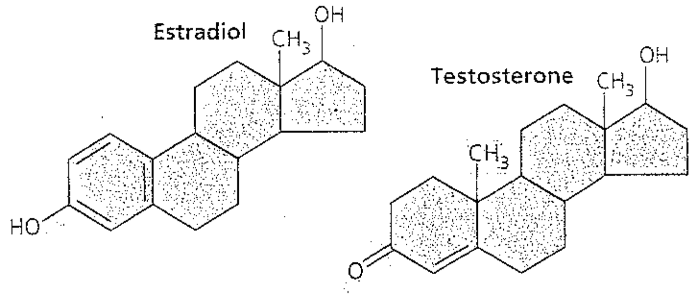
1. Draw a structural formula for C_2H_4.
2. Which molecules in Figure 4.5 are isomers? For each pair, identify the type of isomer.
3. How are gasoline and fat chemically similar?
4. **WHAT IF?** Can propane (C_3H_8) form isomers?

For suggested answers, see Appendix A.

CONCEPT 4.3

A small number of chemical groups are key to the functioning of biological molecules

The distinctive properties of an organic molecule depend not only on the arrangement of its carbon skeleton but also on the molecular components attached to that skeleton. We can think of hydrocarbons, the simplest organic molecules, as the underlying framework for more complex organic molecules. A number of chemical groups can replace one or more of the hydrogens bonded to the carbon skeleton of the hydrocarbon. (Some groups include atoms of the carbon skeleton, as we will see.) These groups may participate in chemical reactions or may contribute to function indirectly by their effects on molecular shape. The number and arrangement of the groups help give each molecule its unique properties.



▲ **Figure 4.9 A comparison of chemical groups of female (estradiol) and male (testosterone) sex hormones.** The two molecules differ only in the chemical groups attached to a common carbon skeleton of four fused rings, shown here in abbreviated form. These subtle variations in molecular architecture (shaded in blue) influence the development of the anatomical and physiological differences between female and male vertebrates.

The Chemical Groups Most Important in the Processes of Life

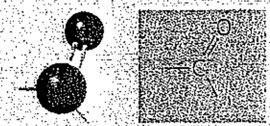
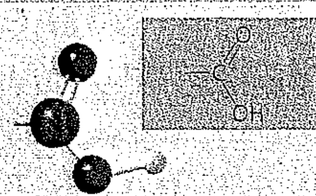
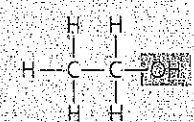
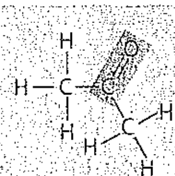
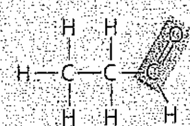
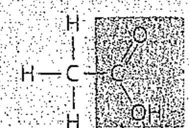
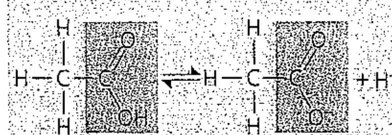
Consider the differences between testosterone and estradiol (a type of estrogen). These compounds are male and female sex hormones, respectively, in humans and other vertebrates (**Figure 4.9**). Both are steroids, organic molecules with a common carbon skeleton in the form of four fused rings. These sex hormones differ only in the chemical groups attached to the rings. The different actions of these two molecules on many targets throughout the body help produce the contrasting features of males and females. Thus, even our sexuality has its biological basis in variations of molecular architecture.

In the example of sex hormones, different chemical groups contribute to function by affecting the molecule's shape. In other cases, the chemical groups affect molecular function by being directly involved in chemical reactions; these important chemical groups are known as **functional groups**. Each functional group participates in chemical reactions in a characteristic way, from one organic molecule to another.

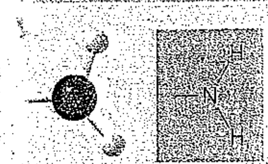
The seven chemical groups most important in biological processes are the hydroxyl, carbonyl, carboxyl, amino, sulfhydryl, phosphate, and methyl groups. The first six groups can act as functional groups; they are also hydrophilic and thus increase the solubility of organic compounds in water. The methyl group is not reactive, but instead often acts as a recognizable tag on biological molecules. Before reading further, study **Figure 4.10** on the next two pages to familiarize yourself with these biologically important chemical groups.

▼ Figure 4.10

Exploring Some Biologically Important Chemical Groups

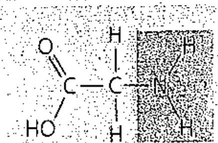
CHEMICAL GROUP	Hydroxyl	Carbonyl	Carboxyl
STRUCTURE	 (may be written HO—) In a **hydroxyl group** (—OH), a hydrogen atom is bonded to an oxygen atom, which in turn is bonded to the carbon skeleton of the organic molecule. (Do not confuse this functional group with the hydroxide ion, OH^-.)	 The **carbonyl group** (>CO) consists of a carbon atom joined to an oxygen atom by a double bond.	 When an oxygen atom is double-bonded to a carbon atom that is also bonded to an —OH group, the entire assembly of atoms is called a **carboxyl group** (—COOH).
NAME OF COMPOUND	**Alcohols** (their specific names usually end in *-ol*)	**Ketones** if the carbonyl group is within a carbon skeleton **Aldehydes** if the carbonyl group is at the end of the carbon skeleton	**Carboxylic acids**, or organic acids
EXAMPLE	 **Ethanol**, the alcohol present in alcoholic beverages	 **Acetone**, the simplest ketone  **Propanal**, an aldehyde	 **Acetic acid**, which gives vinegar its sour taste
FUNCTIONAL PROPERTIES	• Is polar as a result of the electrons spending more time near the electronegative oxygen atom. • Can form hydrogen bonds with water molecules, helping dissolve organic compounds such as sugars (see Figure 5.3).	• A ketone and an aldehyde may be structural isomers with different properties, as is the case for acetone and propanal. • These two groups are also found in sugars, giving rise to two major groups of sugars: aldoses (containing an aldehyde) and ketoses (containing a ketone).	• Has acidic properties (is a source of hydrogen ions) because the covalent bond between oxygen and hydrogen is so polar; for example,  Acetic acid Acetate ion • Found in cells in the ionized form with a charge of 1− and called a carboxylate ion (here, specifically, the acetate ion).

Amino



The **amino group** ($—NH_2$) consists of a nitrogen atom bonded to two hydrogen atoms and to the carbon skeleton.

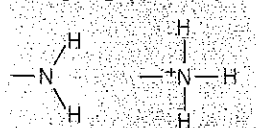
Amines



Glycine

Because it also has a carboxyl group, glycine is both an amine and a carboxylic acid; compounds with both groups are called **amino acids.**

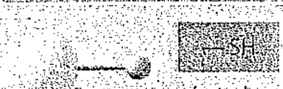
- Acts as a base; can pick up an H^+ from the surrounding solution (water, in living organisms).



(nonionized) (ionized)

- Ionized, with a charge of 1+, under cellular conditions.

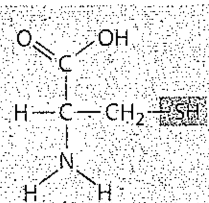
Sulfhydryl



(may be written HS—)

The **sulfhydryl group** consists of a sulfur atom bonded to an atom of hydrogen; resembles a hydroxyl group in shape.

Thiols

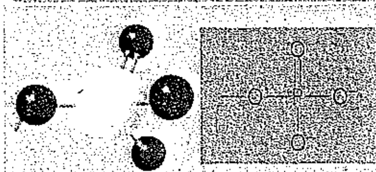


Cysteine

Cysteine is an important sulfur-containing amino acid.

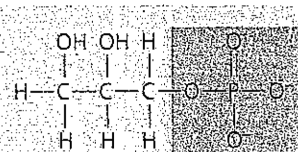
- Two sulfhydryl groups can react, forming a covalent bond. This "cross-linking" helps stabilize protein structure (see Figure 5.21).
- Cross-linking of cysteines in hair proteins maintains the curliness or straightness of hair. Straight hair can be "permanently" curled by shaping it around curlers, then breaking and re-forming the cross-linking bonds.

Phosphate



In a **phosphate group**, a phosphorus atom is bonded to four oxygen atoms; one oxygen is bonded to the carbon skeleton; two oxygens carry negative charges. The phosphate group ($—OPO_3^{2-}$, abbreviated Ⓟ) is an ionized form of a phosphoric acid group ($—OPO_3H_2$; note the two hydrogens).

Organic phosphates

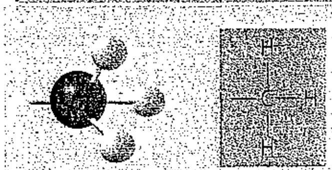


Glycerol phosphate

In addition to taking part in many important chemical reactions in cells, glycerol phosphate provides the backbone for phospholipids, the most prevalent molecules in cell membranes.

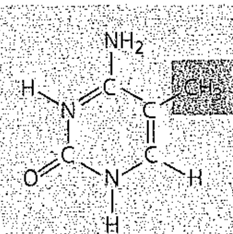
- Contributes negative charge to the molecule of which it is a part (2– when at the end of a molecule, as above; 1– when located internally in a chain of phosphates).
- Has the potential to react with water, releasing energy.

Methyl



A **methyl group** consists of a carbon bonded to three hydrogen atoms. The methyl group may be attached to a carbon or to a different atom.

Methylated compounds



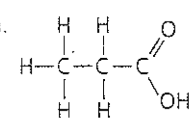
5-Methyl cytidine

5-Methyl cytidine is a component of DNA that has been modified by addition of the methyl group.

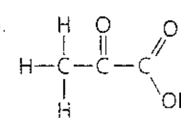
- Addition of a methyl group to DNA, or to molecules bound to DNA, affects expression of genes.
- Arrangement of methyl groups in male and female sex hormones affects their shape and function (see Figure 4.9).

Given the information in this figure and what you know about the electronegativity of oxygen, predict which of the following molecules would be the stronger acid. Explain your answer.

a.

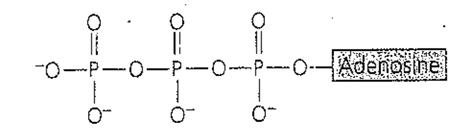


b.

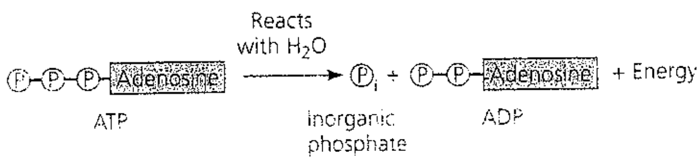


ATP: An Important Source of Energy for Cellular Processes

The "Phosphate" column in Figure 4.10 shows a simple example of an organic phosphate molecule. A more complicated organic phosphate, **adenosine triphosphate**, or ATP, is worth mentioning because its function in the cell is so important. ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups:



Where three phosphates are present in series, as in ATP, one phosphate may be split off as a result of a reaction with water. This inorganic phosphate ion, $HOPO_3^{2-}$, is often abbreviated $Ⓟ_i$ in this book. Having lost one phosphate, ATP becomes adenosine *di*phosphate, or ADP. Although ATP is sometimes said to "store" energy, it is more accurate to think of it as "storing" the potential to react with water. This reaction releases energy that can be used by the cell. You will learn about this in more detail in Chapter 8.



CONCEPT CHECK 4.3

1. What does the term *amino acid* signify about the structure of such a molecule?
2. What chemical change occurs when ATP reacts with water and releases energy?
3. **WHAT IF?** Suppose you had an organic molecule such as glycine (see Figure 4.10, amino group example), and you chemically removed the —NH_2 group and replaced it with —COOH. Draw the structural formula for this molecule and speculate about its chemical properties.

For suggested answers, see Appendix A.

The Chemical Elements of Life: *A Review*

Living matter, as you have learned, consists mainly of carbon, oxygen, hydrogen, and nitrogen, with smaller amounts of sulfur and phosphorus. These elements all form strong covalent bonds, an essential characteristic in the architecture of complex organic molecules. Of all these elements, carbon is the virtuoso of the covalent bond. The versatility of carbon makes possible the great diversity of organic molecules, each with particular properties that emerge from the unique arrangement of its carbon skeleton and the chemical groups appended to that skeleton. At the foundation of all biological diversity lies this variation at the molecular level.

Chapter 4 Review

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SUMMARY OF KEY CONCEPTS

CONCEPT 4.1

Organic chemistry is the study of carbon compounds (pp. 58–59)

- Organic compounds were once thought to arise only within living organisms, but this idea (vitalism) was disproved when chemists were able to synthesize organic compounds in the laboratory.

CONCEPT 4.2

Carbon atoms can form diverse molecules by bonding to four other atoms (pp. 60–63)

- **The Formation of Bonds with Carbon** Carbon, with a valence of 4, can bond to various other atoms, including O, H, and N. Carbon can also bond to other carbon atoms, forming the carbon skeletons of organic compounds.
- **Molecular Diversity Arising from Carbon Skeleton Variation** The carbon skeletons of organic molecules vary in length and shape and have bonding sites for atoms of other elements. Hydrocarbons consist only of carbon and hydrogen. Isomers are compounds with the same molecular formula but different structures and properties. Three types of isomers are structural isomers, geometric isomers, and enantiomers.

MEDIA

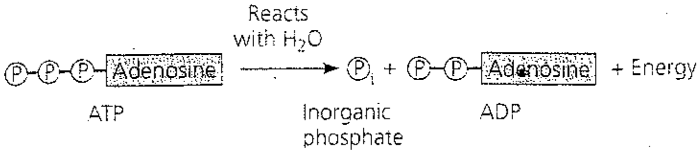
Activity Diversity of Carbon-Based Molecules
Activity Isomers
Investigation What Factors Determine the Effectiveness of Drugs?

CONCEPT 4.3

A small number of chemical groups are key to the functioning of biological molecules (pp. 63–66)

- **The Chemical Groups Most Important in the Processes of Life** Chemical groups attached to the carbon skeletons of organic molecules participate in chemical reactions (functional groups) or contribute to function by affecting molecular shape.

▶ **ATP: An Important Source of Energy for Cellular Processes**



MEDIA
Activity Functional Groups

▶ **The Chemical Elements of Life: *A Review*** Living matter is made mostly of carbon, oxygen, hydrogen, and nitrogen, with some sulfur and phosphorus. Biological diversity has its molecular basis in carbon's ability to form a huge number of molecules with particular shapes and chemical properties.

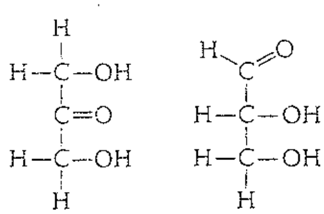
TESTING YOUR KNOWLEDGE

SELF-QUIZ

1. Organic chemistry is currently defined as
   a. the study of compounds made only by living cells.
   b. the study of carbon compounds.
   c. the study of vital forces.
   d. the study of natural (as opposed to synthetic) compounds.
   e. the study of hydrocarbons.

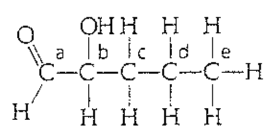
2. Which of the following hydrocarbons has a double bond in its carbon skeleton?
   a. C_3H_8
   b. C_2H_6
   c. CH_4
   d. C_2H_4
   e. C_2H_2

3. Choose the term that correctly describes the relationship between these two sugar molecules:

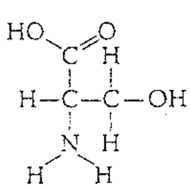


   a. structural isomers
   b. geometric isomers
   c. enantiomers
   d. isotopes

4. Identify the asymmetric carbon in this molecule:



5. Which functional group is *not* present in this molecule?



   a. carboxyl
   b. sulfhydryl
   c. hydroxyl
   d. amino

6. Which action could produce a carbonyl group?
   a. the replacement of the —OH of a carboxyl group with hydrogen
   b. the addition of a thiol to a hydroxyl
   c. the addition of a hydroxyl to a phosphate
   d. the replacement of the nitrogen of an amine with oxygen
   e. the addition of a sulfhydryl to a carboxyl

7. Which chemical group is most likely to be responsible for an organic molecule behaving as a base?
   a. hydroxyl
   b. carbonyl
   c. carboxyl
   d. amino
   e. phosphate

For Self-Quiz answers, see Appendix A.

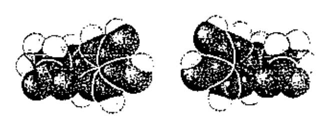
MEDIA Visit **www.campbellbiology.com** for a Practice Test.

EVOLUTION CONNECTION

8. **DRAW IT** Some scientists believe that life elsewhere in the universe might be based on the element silicon, rather than on carbon, as on Earth. Look at the electron distribution diagram for silicon in Figure 2.9 and draw the Lewis dot structure for silicon. What properties does silicon share with carbon that would make silicon-based life more likely than, say, neon-based life or aluminum-based life?

SCIENTIFIC INQUIRY

9. In 1918, an epidemic of sleeping sickness caused an unusual rigid paralysis in some survivors, similar to symptoms of advanced Parkinson's disease. Years later, L-dopa (below, left), a chemical used to treat Parkinson's disease, was given to some of these patients, as dramatized in the movie *Awakenings*. L-dopa was remarkably effective at eliminating the paralysis, at least temporarily. However, its enantiomer, D-dopa (right), was subsequently shown to have no effect at all, as is the case for Parkinson's disease. Suggest a hypothesis to explain why, for both diseases, one enantiomer is effective and the other is not.



L-dopa D-dopa

SCIENCE, TECHNOLOGY, AND SOCIETY

10. Thalidomide achieved notoriety 50 years ago because of a wave of birth defects among children born to women who took thalidomide during pregnancy as a treatment for morning sickness. However, in 1998 the U.S. Food and Drug Administration (FDA) approved this drug for the treatment of certain conditions associated with Hansen's disease (leprosy). In clinical trials, thalidomide also shows promise for use in treating patients suffering from AIDS, tuberculosis, and some types of cancer. Do you think approval of this drug is appropriate? If so, under what conditions? What criteria do you think the FDA should use in weighing a drug's benefits against its dangers?