5

The Nature of Life on Earth

LEARNING GOALS

5.1 DEFINING LIFE
- What are the general properties of life on Earth?
- What is the role of evolution in defining life?
- What is life?

5.2 CELLS: THE BASIC UNITS OF LIFE
- What are living cells?
- What are the molecular components of cells?
- What are the major groupings of life on Earth?

5.3 METABOLISM: THE CHEMISTRY OF LIFE
- What are the basic metabolic needs of life?
- How do we classify life by its metabolic sources?

5.4 DNA AND HEREDITY
- How does the structure of DNA allow for its replication?
- How is heredity encoded in DNA?
- How does life evolve?

5.5 LIFE AT THE EXTREME
- What kinds of conditions can life survive?
- Are extremophiles really extreme?

THE PROCESS OF SCIENCE IN ACTION

5.6 EVOLUTION AS SCIENCE
- Is evolution a fact or a theory?
- Are there scientific alternatives to evolution?

Having talked about the conditions that make life possible on Earth, we are now ready to begin talking about the nature of life and its interactions with a planetary environment. As with many aspects of astrobiology, we are limited by the fact that we have only one example to study: life on Earth. Although it's possible that life elsewhere could be quite different, the great diversity of life on Earth gives us plenty to study here. And anything we learn about life on this world can help us understand the possibilities for other worlds.

In this chapter, we'll explore the general nature of life on Earth. Along the way, we'll see that life elsewhere would almost certainly share at least a few characteristics with life on Earth, and we'll gain a few clues about where we might most profitably focus our search for life in the universe.

There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.

Charles Darwin, *The Origin of Species*, 1859

5.1 Defining Life

What is life? This seemingly simple question lies at the heart of research into life in the universe. After all, if we are interested in the possibility of life elsewhere, we must know what it is that we are looking for. Unfortunately, defining life is surprisingly difficult, even when we consider only life on Earth. Life on Earth is remarkably diverse; organisms range in size from tiny microbes to huge plants and animals, and can be found thriving in almost every conceivable place on and near our planet's surface. Defining life is all the more difficult when we consider life elsewhere, because we cannot be sure that life on other worlds would resemble life on Earth physically or chemically. Given the difficulty of defining life, the only sensible way to proceed is by studying the one example of life that we know, hoping it will yield fundamental insights into how life operates and into the environmental conditions required to support life. In this first section, we will explore general characteristics of life on Earth and attempt to come up with at least some reasonably useful definition of life.

• What are the general properties of life on Earth?

A cat and a car have much in common. Both require energy to function—the cat gets energy from food, and the car gets energy from gasoline. Both can move at varying speeds and can turn corners. Both expel waste products. But a cat clearly is alive, while a car clearly is not. What's the difference?

In the case of a cat and a car, we can find many important differences without looking too far. For example, cats reproduce themselves, while cars must be built in factories. But as we look deeper into the nature of life, it becomes increasingly difficult to decide what characteristics separate living organisms from rocks and other nonliving materials. Indeed, the question can be so difficult to answer that we may be tempted to fall back on the famous words of U.S. Supreme Court Justice Potter Stewart, who, in avoiding the difficulty of defining pornography, wrote: "I shall not today attempt further to define [it]. . . . But I know it when I see it."* If living organisms on other worlds turn out to be much like those on Earth, it may prove true that we'll know them when we see them. But if the organisms are fairly different from those on Earth, we'll need clearer guidelines to decide whether or not they are truly "living."

One way to seek distinguishing features of life is to study living organisms, looking for common characteristics. Given the difficulty of defining life, you probably won't be surprised to learn that there are exceptions to almost any "rule" we think of. Nevertheless, biologists have identified at least six key properties that appear to be shared by most or all living organisms on Earth, all of which are summarized in Figure 5.1. Let's briefly investigate each property.

ORDER The materials in living organisms always exhibit some type of order. For example, the molecules in living cells are not scattered randomly about but instead are arranged in patterns that make cell structures. These structures, in turn, make possible all the other properties of life that we will discuss. Note that order alone does not make something living: A book has order, because words are not scattered randomly on the pages, but it is not alive. The same is true for rock crystals, whose atoms are arranged in an orderly way, and even for the individual molecules of life such as proteins or DNA; these molecules clearly have order, but we consider them only to be building blocks of life, not life itself.

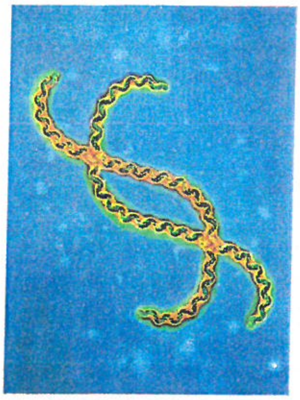
Nevertheless, it seems reasonable to expect that all living things will show order. In logical terms, we say that order is a *necessary condition* for life, because something cannot be alive without order. However, order is not a *sufficient condition* for life, because order alone does not make something alive.

Think About It The idea of necessary and sufficient conditions is important in science. To make sure you understand it, decide whether each of the following conditions is necessary or sufficient (or neither or both) for the given effect: (a) condition: breathing; effect: human survival while sleeping; (b) condition: living in New York City; effect: living in the United States; (c) condition: meeting all requirements for a college degree; effect: receiving a college degree.

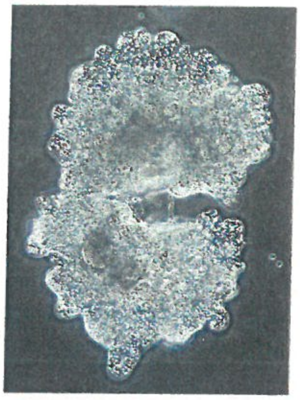
REPRODUCTION Living organisms reproduce or are products of reproduction. Simple life-forms, such as bacteria, reproduce by dividing to make nearly exact copies of themselves. More complex organisms may reproduce in more sophisticated ways—including sexual reproduction, in which offspring inherit genetic material from two parents. Note that not all living organisms are capable of reproduction. For example, a mule is sterile and cannot reproduce. However, the mule still meets the reproduction criterion because it is the product of reproduction between two closely related animals (a horse and a donkey).

*From Potter Stewart's concurring opinion in *Jacobellis v. Ohio*, 378 U.S. 184, 198 (1964).

Figure 5.1
Six key properties of life.



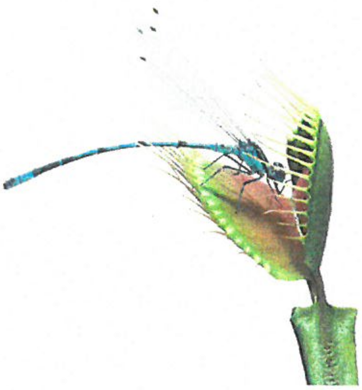
a Order: Living organisms exhibit order in their internal structure, as is apparent in this microscopic view of spiral patterns in two single-celled organisms.



b Reproduction: Organisms reproduce their own kind. Here, a single-celled organism (an amoeba) has already copied its genetic material (DNA) and is now dividing into two cells.

c Growth and development: Living organisms grow and develop in patterns determined at least in part by heredity. Here, we see a Nile crocodile hatching from an egg.

d Energy utilization: Living organisms use energy to fuel their many activities. These tube worms, which live near a deep-sea volcanic vent, obtain energy from chemical reactions made possible in part by the heat released from the vent.



e Response to the environment: Life actively responds to changes in its surroundings. Here, we see a Venus flytrap closing in response to being touched by an insect.

f Evolutionary adaptation: Life evolves in a way that leads to organisms that are adapted to their environments. Here, we see a katydid with camouflage that evolved to hide it among leaves.

Reproduction seems necessary to any definition of life; without it, there would be no way for life as a whole to survive the death of individuals. However, it also exposes borderline cases about which even scientists disagree. For example, *viruses* are generally much smaller than bacteria and are incapable of reproducing on their own. However, when a virus infects a living organism, it can reproduce by commandeering the organism's reproductive machinery for its own purposes. The fact that viruses can reproduce when they infect other organisms but not when they are on their own seems to put them somewhere between the nonliving and the living. Another borderline case concerns the infectious proteins known as *prions,* which are thought to be the agents of *mad cow disease.* Prions appear to be abnormal forms of protein molecules that somehow cause normal protein molecules to change into the abnormal prion form. In other words, they make copies of themselves by causing other molecules to change rather than by actually replicating themselves. Most biologists therefore put them on the nonliving side of the gray region between nonlife and life, though they present at least some ambiguity.

GROWTH AND DEVELOPMENT Living organisms grow and develop in patterns directed at least in part by **heredity**—traits passed to an organism from its parent(s). The property of growth and development appears necessary to life in that all organisms grow or develop during at least some periods in their life cycles, but it is not sufficient to constitute life. For example, fire grows and develops as it spreads through a forest, but a fire is not alive. As we will discuss later in this chapter, all life on

KEY BIOLOGICAL DEFINITIONS

TERMS RELATED TO EVOLUTION:

evolution (biological): The gradual change in populations of living organisms that has transformed life on Earth from its primitive origins to the great diversity of life today.

evolutionary adaptation: An inherited trait that enhances an organism's ability to survive and reproduce in a particular environment.

theory of evolution: The theory, first advanced by Charles Darwin, that explains how and why living organisms evolve through time.

natural selection: The primary mechanism by which evolution proceeds. More specifically, natural selection refers to the process by which, over time, advantageous genetic traits naturally win out (are "selected") over less advantageous traits because they are more likely to be passed down through succeeding generations.

species: Precise definitions vary, but for our purposes we can consider a species to be a population of organisms that is genetically distinct from other groups of organisms.

TERMS RELATED TO HEREDITY:

heredity: The characteristics of an organism passed to it by its parent(s), which it can pass on to its offspring. The term can also apply to the transmission of these characteristics from one generation to the next. Hereditary information is encoded in DNA.

gene: The basic functional unit of an organism's heredity. A single gene consists of a sequence of DNA bases (or RNA bases, in some viruses) that provides the instructions for a single cell function (such as building a protein).

genome: The complete sequence of DNA bases in an organism, encompassing all of the organism's genes along with noncoding DNA in between.

genetic code: The specific set of rules by which the sequence of bases in DNA is "read" to provide the instructions that make up genes.

DNA (deoxyribonucleic acid): The basic hereditary molecule of life on Earth. A DNA molecule consists of two strands, twisted in the shape of a double helix, along each of which lies a long sequence of *DNA bases.* The four DNA bases are adenine (A), cytosine (C), guanine (G), and thymine (T), and they can be paired across the two DNA strands only so that A pairs with T and C pairs with G.

RNA (ribonucleic acid): A molecule closely related to DNA, but with only a single strand and a slightly different backbone and set of bases; RNA plays many crucial roles in cells.

TERMS RELATED TO THE MODERN CLASSIFICATION OF LIFE:

cell: The basic structure of all life on Earth, in which the living matter inside is separated from the outside world by a barrier called a *membrane.*

domains of life: All known species of life fall into one of three broad domains: *bacteria, archaea,* and *eukarya;* the last includes all plants and animals, as well as fungi and many microbes.

tree of life: A representation of biochemical and genetic relationships between species; the three major branches of the tree are the three domains (bacteria, archaea, and eukarya).

TERMS RELATED TO CELLULAR CHEMISTRY:

organic molecule: Generally, any molecule containing carbon and associated with life. Note that we do not generally consider molecules such as carbon dioxide (CO_2) and carbonate minerals to be organic, since they are commonly found independent of life.

organic chemistry: The chemistry of organic molecules.

biochemistry: The chemistry of life.

amino acids: The molecules that form the building blocks of proteins. Most organisms construct proteins from a particular set of 20 amino acids, although several dozen other amino acids can be found in nature. More technically, an amino acid is a molecule containing both an *amino group* (NH or NH_2) and a *carboxyl group* (COOH).

protein: A large molecule assembled from amino acids according to instructions encoded in DNA. Proteins play many roles in cells; a special category of proteins, called **enzymes,** catalyzes nearly all the important biochemical reactions that occur within cells.

catalysis: The process of causing or accelerating a chemical reaction by involving a substance or molecule that is not permanently changed by the reaction. The unchanged substance or molecule involved in catalysis is called a **catalyst.** In living cells, the most important catalysts are the proteins known as *enzymes.*

metabolism: The many chemical reactions that occur in living organisms to provide cellular energy and nutrients.

Earth passes on its heredity through the molecules known as DNA. (Some viruses use a related molecule called RNA, but we will leave viruses and prions out as we discuss "life" in the rest of this chapter.)

ENERGY UTILIZATION Living organisms use energy to create and maintain patterns of order within their cells, to reproduce, and to grow. Life without energy utilization is simply not possible (though some organisms can survive temporarily in dormant states). Of course, energy utilization is not sufficient to constitute life; any electrical or gas-powered appliance uses energy to function.

We can gain further insight into the importance of energy utilization by considering what is sometimes called the *thermodynamics* of life. Thermodynamics is a branch of science that deals with energy and the rules by which it operates. Recall the *law of conservation of energy* [Section 3.4], which tells us that energy can be neither created nor destroyed but only transformed from one form to another; this law is sometimes referred to as the "first law of thermodynamics." The **second law of thermodynamics** states that, when left alone, the energy in a system undergoes conversions that lead to increasing disorder. Living organisms are a perfect example of this law's importance: If you place a living organism into a sealed box, it will eventually use up the available energy and therefore no longer be able to build new molecules or fuel any of the molecular processes needed for life. Its molecules will then become more disordered with time—for example, the molecules may decay or may lose the orderly relationships they maintain with other molecules when the organism is alive—causing the organism to die. To maintain order and survive, a living organism must have a continual source of energy that it can use to counter the tendency for disorder to take over. Living organisms get this energy from the environment, either through food or through chemical interactions with the environment. The environment, in turn, gets its energy either from an internal source, such as the heat of the planet itself, or from an external source, such as sunlight. Thus, life probably is not possible on a world that lacks a long-term source of energy input to the environment.

RESPONSE TO THE ENVIRONMENT All living organisms interact with their surroundings and actively respond in at least some ways to environmental changes. For example, some simple organisms may move to a region where the temperature is more suited to their growth, and warm-blooded mammals may sweat, pant, or adjust blood flow to maintain a constant internal temperature. Like all the other properties on our list, response to the environment is a necessary but not sufficient condition for life. Many human-made devices also respond to changes in the environment; for example, a thermostat can respond to changes in temperature by turning on heating or cooling systems.

EVOLUTIONARY ADAPTATION Life has changed dramatically over time as the organisms that lived billions of years ago have gradually evolved into the great variety of organisms found on Earth today. Life evolves as a result of the interactions between organisms and their environments, leading over time to evolutionary adaptations that make species better suited to their environments. When the adaptations are significant enough, organisms carrying the adaptations may be so different from their ancestors that they constitute an entirely new species.

Before we continue, it's worth noting that, like life itself, the familiar term **species** is not so easy to define in a precise way. Traditionally, a species was defined as a group of organisms that share some set of common characteristics and are capable of interbreeding with one another to produce fertile offspring. Thus, for example, horses and donkeys represent different species because the result of their interbreeding is an infertile mule. However, while this definition of species works fairly well for animals and most plants, it does not work for organisms that reproduce asexually, including microorganisms that reproduce through cell division. As a result, biologists today recognize species as groups of organisms that are genetically distinct from other groups, though the precise border between one species and another is not always clear, especially with microorganisms. Once a species is identified, it is given a scientific name that consists of two parts. The first part is the **genus,** which describes the "generic" category to which the organism belongs, while the second part distinguishes multiple species within the same genus. (You may recognize that the term *genus* is related to "generic" and that the term *species* is related to "specific.") The full name is always written in italics, with the genus capitalized. For example, humans are scientifically classified as *Homo sapiens,* meaning that we are one specific species that has been identified within the genus *Homo* (the others are all extinct). Horses and donkeys are, respectively, *Equus caballus* and *Equus asinus,* names that show that both belong to the same genus (*Equus*).

• What is the role of evolution in defining life?

All six properties of life that we have discussed are important, but biologists today regard evolutionary adaptation as the most fundamental and unifying of all these properties. It is the only property that can explain the great diversity of life on Earth, and an understanding of it allows us to understand how all the other properties of life came to be. Modern understanding of the capacity for evolutionary adaptation is described by the **theory of evolution.** Because this theory is so central to modern biology, let's briefly investigate the origin of the theory and the evidence that supports it.

AN ANCIENT IDEA The word *evolution* simply means "change with time," and the idea that life might evolve through time goes back more than 2500 years. The Greek scientist Anaximander (c. 610–547 B.C.) promoted the idea that life originally arose in water and gradually evolved from simpler to more complex forms. A century later, Empedocles (c. 492–432 B.C.) suggested that creatures poorly adapted to their environments would perish, foreshadowing the modern idea of evolutionary adaptation. Many of the early Greek atomists [Section 2.1] probably held similar beliefs, though the evidence is sparse. Aristotle, however, maintained that species are fixed and independent of one another and do not evolve. This Aristotelian view eventually became entrenched within the theology of Christianity, and evolution was not taken seriously again for some 2000 years. In the mid-eighteenth century, scientists began to suspect that many fossils represented extinct ancestors of living species. Then, in the early 1800s, French naturalist Jean Baptiste Lamarck suggested that the best explanation for the relationship between fossils and living organisms is that life-forms evolve by gradually adapting to perform successfully in their environments.

Lamarck's idea of evolution by adaptation represented the first clear attempt to explain what we now consider the "observed facts" of evolution. That is, observations of how fossils differ in different layers of the geological record and of relationships between living species make it quite clear that life has changed over time. However, Lamarck was unable to come up with a successful theory to explain *how* evolution occurs. His hypothesis concerning the mechanism of evolution, called "inheritance of acquired characteristics," suggested that organisms develop new characteristics during their lives and then pass these characteristics on to their offspring. For example, Lamarck would have imagined that weight lifting would enable a person to create an adaptation of great strength that could be genetically passed to his or her children. While this hypothesis may have seemed quite reasonable at the time, it has not stood up to scientific scrutiny and therefore has been discarded as a model of how evolution occurs. It has been replaced by a different model, proposed by the British naturalist Charles Darwin.

THE MECHANISM OF EVOLUTION Charles Darwin described his theory of evolution in his book *The Origin of Species,* first published in 1859. In this book, Darwin laid out the case for evolution in two fundamental ways. First, he described his observations of living organisms (made during his voyages on the HMS *Beagle*) and showed how they supported the idea that evolutionary change really does occur. Second, he put forth a new model of *how* evolution occurs, backing up his model with a wealth of evidence. In essence, the geological record and the observed relationships between species together provide strong evidence that evolution *has* occurred, while Darwin's theory of evolution explains *how* it occurs.

As is the case with most scientific theories, the underlying logic of Darwin's model is really quite simple. As biologist Stephen Jay Gould (1941–2002) described, Darwin built his model from "two undeniable facts and an inescapable conclusion":

- *Fact 1: overproduction and competition for survival.* Any localized population of a species has the potential to produce far more offspring than the local environment can support with resources such as food and shelter. This overproduction leads to a competition for survival among the individuals of the population.
- *Fact 2: individual variation.* Individuals in a population of any species vary in many heritable traits (traits passed from parents to offspring). No two individuals are exactly alike, and some individuals possess traits that make them better able to compete for food and other vital resources.
- *The inescapable conclusion: unequal reproductive success.* In the struggle for survival, those individuals whose traits best enable them to survive and reproduce will, on average, leave the largest number of offspring that in turn survive to reproduce. Therefore, in any local environment, heritable traits that enhance survival and successful reproduction will become progressively more common in succeeding generations.

It is this unequal reproductive success that Darwin called **natural selection:** Over time, advantageous genetic traits will naturally win out (be "selected") over less advantageous traits because they are more likely to be passed down through many generations. This process explains how species can change in response to their environment—by favoring traits that improve adaptation—and thus is the primary mechanism of evolution.

EVIDENCE FOR EVOLUTION BY NATURAL SELECTION Darwin backed up his logical claim that evolution proceeds through natural selection by documenting cases in which related organisms are adapted to different environments or lifestyles. He found a particularly striking example among the finches of the Galápagos Islands (Figure 5.2), where different islands have different species, with each species adapted to its particular environment. Darwin realized that natural selection could explain this situation. He presumed that an ancestral pair of finches reached the Galápagos from the mainland (perhaps by being blown off course by winds). Over time, local populations of island finches gradually adapted to become the distinct species that he observed.

Darwin recognized similar patterns among many other species in the Galápagos and elsewhere in his round-the-world voyage. He also discovered fossils of extinct organisms that were clearly related to modern organisms, yet different in key respects. For example, in Brazil he found fossils of giant armadillos that he realized must be the ancestors of the modern armadillos found in the same region. The pieces of the puzzle gradually came together in Darwin's mind: He realized that natural selection not only explained the differences between closely related modern species like the finches, but also explained the fact that larger changes can occur over longer periods of time, with the result that entire species can become extinct and new ones can take their places.

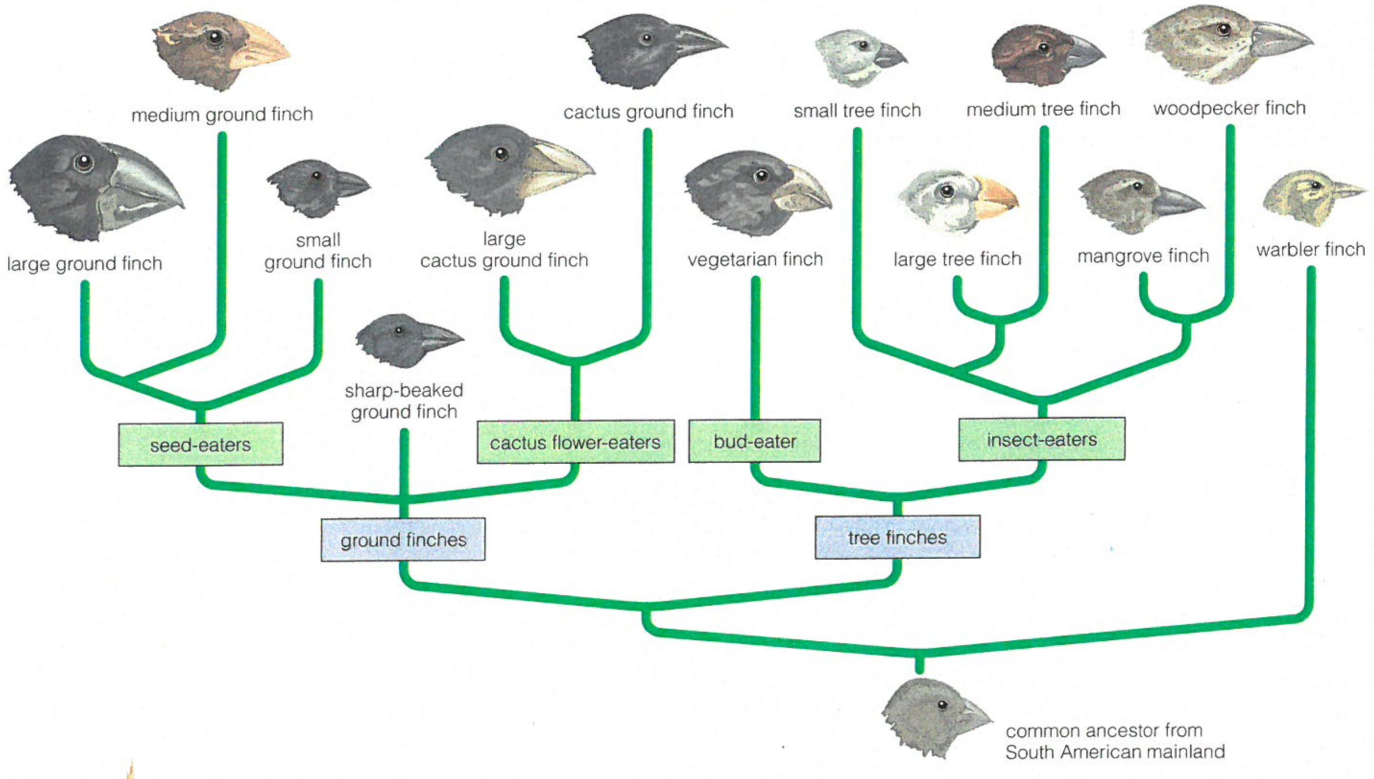


Figure 5.2
An evolutionary tree for the 13 species of Galápagos finches. These finch species are all closely related descendants of a common ancestor from the South American mainland. Note the diversity of beaks, which are adapted to certain food sources on the different islands. (Courtesy of Campbell, Reece, *Biology*.)

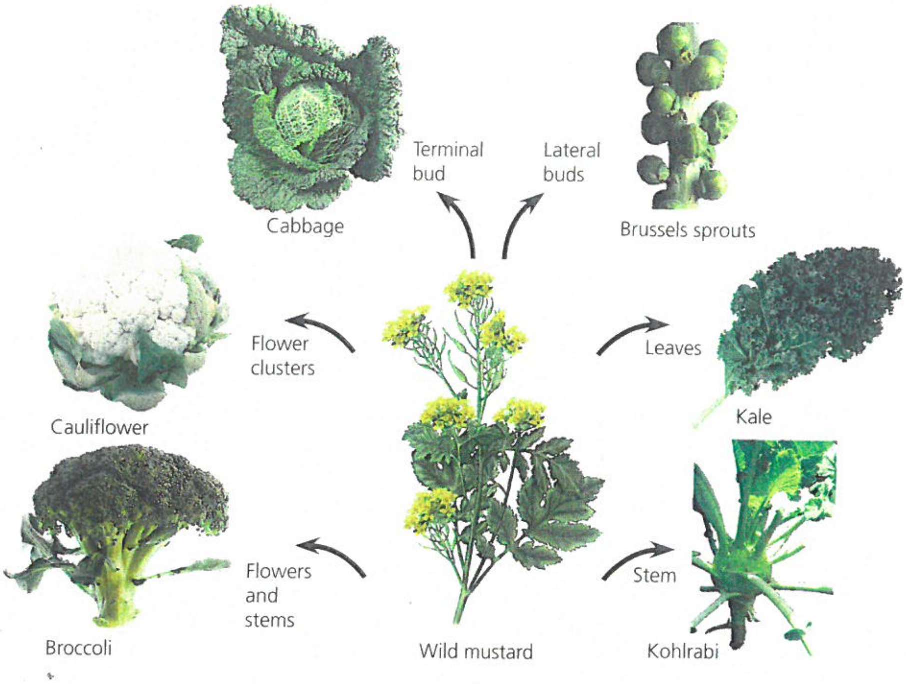


Figure 5.3

The six vegetables shown all look and taste quite different, but they were all bred by humans from the same wild ancestor (wild mustard). This is an example of artificial selection, which is much like natural selection except that humans (rather than nature) decide which individuals in each generation survive and breed offspring. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

Darwin also found strong support for his theory of evolution by looking at examples of *artificial selection*—the selective breeding of domesticated plants or animals by humans. Over the past few thousand years, humans have gradually bred many plants and animals into forms that bear little resemblance to their wild ancestors. Figure 5.3 shows how artificial selection has created a variety of vegetables from a single common ancestor. Similarly, dogs as different as Rottweilers and Chihuahuas were bred from a common ancestor within just a few thousand years. Darwin recognized that if artificial selection could cause such profound changes in just a few thousand years, natural selection could do far more over many millions of years.

Today, we can observe natural selection occurring right before our eyes. In many places on Earth, species have changed in time spans as short as a few decades in response to human-induced environmental changes. On a microbial level, natural selection is what allows a population of bacteria to become resistant to specific antibiotics; those few bacteria that acquire a genetic trait of resistance are the only ones that survive in the presence of the antibiotic. Indeed, bacterial cases of natural selection pose a difficult problem for modern medicine, because bacteria can quickly develop resistance to almost any new drug we produce. As a result, pharmaceutical companies are continually working to develop new antibiotics as bacteria become resistant to existing ones. Viruses can evolve even faster, which is one reason it has proved so difficult to fight viral diseases such as influenza and AIDS.

THE MOLECULAR BASIS OF EVOLUTION Darwin's theory of evolution by natural selection tells us that species adapt and change by passing hereditary traits from one generation to the next. However, Darwin did not know precisely how these traits were communicated across generations, nor did he know why there is always variation among individuals or how new traits can appear in a population. Today, thanks to discoveries in molecular biology made since Darwin's time, we know the answers to all these questions. In particular, we now know that organisms are built from instructions contained in a molecule called **DNA** (short for "*d*eoxyribo*n*ucleic *a*cid"), and biologists can now trace how evolutionary adaptations are related to changes that occur through time in DNA. We'll discuss how DNA makes evolutionary adaptations possible when we discuss its structure and function in Section 5.4, but for now the key point is that our understanding of DNA means that we understand the specific mechanisms by which natural selection occurs.

Our detailed understanding of how evolution proceeds on a molecular level, coupled with all the evidence for evolution collected by Darwin and others, puts the theory of evolution by natural selection on a solid foundation. That is, it is a *scientific theory* [Section 2.3] that has withstood countless tests and challenges. Like any scientific theory, the theory of evolution can never be proved beyond all doubt. However, as we'll discuss further in Section 5.6, no credible scientific alternative to the theory of evolution has been proposed, and the evidence in the theory's favor is overwhelming. Indeed, it is difficult to imagine any aspect of biological science that can be understood without being examined in the context of the theory of evolution. That is why evolution has become the unifying theme of all modern biology.

Think About It The idea that life changes through time is quite ancient, and it was already well supported by observations of fossils before Darwin was even born. Moreover, Lamarck recognized that evolution occurs as a result of adaptations about a half-century before Darwin advanced the idea of natural selection. Given these facts, explain why we credit Darwin with the theory of evolution.

SPECIAL TOPIC: Charles Darwin and the Theory of Evolution

Charles Robert Darwin was born into a wealthy and educated family in England on February 12, 1809. His father was a physician, and he had two famous grandfathers. His paternal grandfather, Erasmus Darwin (1731–1802), was a renowned physician and scientist who was a strong proponent of the idea that life evolved gradually. His maternal grandfather, Josiah Wedgwood, started the famous Wedgwood Pottery and China company that still bears his name. Darwin's mother died when he was just 8 years old, but his father and his extended family provided him with a generally happy childhood.

At his father's urging, Darwin enrolled in medical school at age 16. However, he was so horrified by the sight of operations, then done without anesthesia, that he left after just 2 years. He next enrolled in Christ College at Cambridge University, intending to become a minister. While there, he began to indulge a childhood love for the study of nature. Shortly after graduating in 1831, Darwin was offered the opportunity to serve as the naturalist aboard a ship of exploration—the HMS *Beagle*. Darwin was 22 years old when the *Beagle* set sail on December 27, 1831. The voyage lasted nearly 5 years.

The *Beagle* spent much of its voyage exploring the coasts of South America and nearby islands. While the crew conducted surveys, Darwin went ashore to observe the geology and life, collecting numerous specimens that he took back to England. He also read extensively during the voyage, and one book proved particularly influential: Charles Lyell's *Principles of Geology*, published in 1830, presented the case for an ancient Earth sculpted by gradual geological processes. Darwin was given the book by a friend who expected Darwin to disagree with its conclusions; instead, Darwin found that his own observations of geology gave further credence to Lyell's theory.

Meanwhile, Darwin became intrigued by the many adaptations he observed among species in varied environments. He was particularly impressed by the animal life he observed during a 5-week stay on the Galápagos Islands, which lie approximately 1000 kilometers (600 miles) due west of the coast of Ecuador in South America. He focused special attention on the Galápagos finches, concluding that the different bird species must have evolved from a common mainland ancestor (see Figure 5.2). However, at the time he returned to England, he still did not understand how the evolutionary changes occurred.

In 1838, Darwin read Thomas Malthus's *An Essay on the Principle of Population*, in which Malthus famously argued that populations are capable of growing too fast for food supplies to support. The essay helped Darwin crystallize the idea of natural selection by making clear that individuals within a population must compete for survival (the idea embodied in Fact 1 on p. 157). He then began intensive study of how humans bred domestic plants and animals, which helped him

• What is life?

Now that we have examined the fundamental properties of life on Earth, let's return to our original goal in this section: Can we come up with a definition of life?

Based on the central role of evolution, our simplest definition might be that *life is something that can reproduce and evolve through natural selection*. This definition is probably sufficient for most practical purposes, but some cases may still challenge this definition. For example, scientists can now write computer programs (lines of computer code) that can reproduce themselves (create additional sets of identical lines of code). By adding programming instructions that allow random changes, so that the programs can compete and change through a computer analog of natural selection, scientists can even make "artificial life" that evolves on a computer.

Think About It Do you think computer programs that can reproduce and evolve are alive? Why or why not? Would your opinion change if these programs evolved to the point where they could write their own computer code or exchange e-mail with us? What if they wrote other programs that operated machinery to build other computers? Do you think it is possible to create true life on a computer?

Another issue with this definition concerns the origin of life. Darwin's theory of evolution does not tell us how the first life got started. For that, as we'll discuss in Chapter 6, we presume there must have been some type of molecular or *chemical evolution* (as opposed to biological evolution) that went on until the first living organism arose. The idea of chemical evolution is no more surprising than that of natural selection—certain chemical processes are energetically favored under certain circumstances, and laboratory experiments show that under the right conditions, chemicals can

SPECIAL TOPIC: Charles Darwin and the Theory of Evolution *continued*

understand the variation in populations (Fact 2 on p. 157). By 1842, Darwin was convinced that natural selection held the key to evolution, and he began to draft the text that would eventually be published as *The Origin of Species*.

Darwin is said to have been a pleasant man. He was an ardent opponent of slavery, and while he was not a feminist by contemporary standards, he believed that women should be treated with dignity and respect. He was deeply concerned with the impact his theory would have on those who believed in the biblical story of creation. That is probably why he did not publish his theory immediately—he wanted to take time building his case, in hopes that his theory would be so strong that it would be accepted by all without anyone taking offense. Indeed, Darwin might have delayed publication indefinitely if not for a manuscript he received from another scientist, Alfred Russel Wallace, on June 18, 1858.

Wallace had been observing geology and life in Indonesia and had independently come to the same conclusion as Darwin: that life evolves through natural selection. After reading Wallace's draft paper, Darwin worried that "all my originality will be smashed." Fortunately, both Darwin and Wallace were willing to share credit. Their first papers on the theory of evolution were read back to back at a scientific meeting in London on July 1, 1858. A little over a year later, Darwin finally published *The Origin of Species*. All 1250 copies in the first printing sold out on the first day. Within a decade, Darwin's theory was accepted by the vast majority of biologists, an acceptance that has grown stronger ever since.

Charles Darwin and his son William, photographed in 1842.

Darwin never had a taste for arguing about evolution, leaving that to other scientists (especially Thomas Huxley, who called himself "Darwin's bulldog"). He continued his scientific work, publishing several more books on evolution and related topics. In his personal life, Darwin married a cousin, Emma. He and Emma had ten children, but two died in infancy and a third died at age 10. Darwin died on April 19, 1882, at the age of 73. A parliamentary petition won him burial in London's Westminster Abbey, where he lies next to Sir Isaac Newton.

evolve in complexity much like life. However, it begs the question of whether we would recognize a clear distinction between, for example, the last case of chemical evolution and the first living organism capable of biological evolution. No one knows the answer; some scientists think there must have been a clear "first" living organism, while others think that the emergence of life may have been marked by a more gradual transition.

The fact that we have such difficulty distinguishing the living from the nonliving on Earth suggests that we should be cautious about constraining our search for life elsewhere. No matter what definition of life we choose, the possibility always remains that we'll someday encounter something that challenges our definition. Nevertheless, the ability to reproduce and evolve through natural selection seems likely to be shared by most, if not all, life in the universe.

5.2 Cells: The Basic Units of Life

Now that we have discussed general properties of life, we are ready to look more specifically at the nature of life on Earth. In this section, we will explore cells, the basic units of life. We will then be prepared to consider in Section 5.3 how cells make use of energy and in Section 5.4 how cells reproduce and evolve.

• What are living cells?

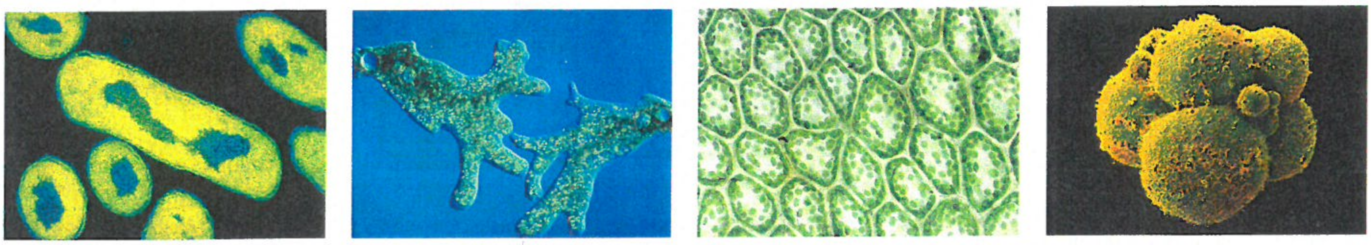
All living organisms are made of **cells**—microscopic units in which the living matter inside is separated from the outside world by a barrier called a **membrane*** (Figure 5.4). Thus, cells are the basic structures of life on Earth. Some organisms consist only of a single cell. Other organisms, like oak trees and people, are complex structures in which trillions of cells work cooperatively, dividing various tasks among specialized cells of different types.

Despite the great diversity of life on Earth, all living cells share a great many similarities. For example, all pass on their hereditary information in the same basic way with DNA, and many other chemical processes are nearly the same in all cells. These similarities, which we'll discuss in more detail later, are profoundly important to our understanding of the origin of life. As far as we know, there is no reason why all living cells must share these characteristics. That is, while life elsewhere might also be

*Some organisms, such as some slime molds, do not perfectly fit this picture of discrete cells, because they consist of a large mass of protoplasm containing thousands of nuclei. Nevertheless, the basic idea that living tissue is contained in a package separated from the external environment still holds.

Figure 5.4

Microscopic views of four types of living cells. In each cell, a membrane separates the living matter inside the cell from the outside world.



a Bacteria **b** Amoebas **c** Plant cells **d** Animal cells composed of cells, we should not expect those cells to have the same biochemistry as cells on Earth. Thus, the many similarities among all cells on our planet suggest a startling conclusion: *All life on Earth shares a common ancestor.* In other words, every living organism on Earth is related to every other one because all evolved over billions of years from the same origin of life.*

EARTH LIFE IS CARBON-BASED Life on Earth is made from more than 20 different chemical elements. However, just four of these elements—oxygen, carbon, hydrogen, and nitrogen—make up about 96% of the mass of typical living cells. Most of the remaining mass consists of just a few other elements, notably calcium, phosphorus, potassium, and sulfur (Figure 5.5).

Given that oxygen dominates Figure 5.5, you might be tempted to say that life on Earth is "oxygen-based." However, most of the oxygen in living cells is found in water molecules (H_2O). The molecules that account for a cell's structure and function owe their remarkable qualities to a different element: carbon. We therefore say that life on Earth is **carbon-based.**

Why is carbon so important to life on Earth? The primary answer to this question lies in how carbon can combine with other elements to make complex molecules. The atoms in any molecule are linked together by **chemical bonds,** which essentially involve sharing of electrons between the individual atoms of a molecule. Different elements can make chemical bonds in different ways. For example, hydrogen atoms generally can bond with only one other atom at a time, while oxygen atoms generally can bond with at most two other atoms at a time. We can see these properties in a water molecule (Figure 5.6): The oxygen atom has two chemical bonds, one to each of the two hydrogen atoms, while each hydrogen atom has only a single chemical bond to the oxygen atom.

Carbon is a particularly versatile chemical element because it can bond to as many as four atoms at a time. This allows carbon atoms to link together in an endless variety of carbon "skeletons" varying in size and branching patterns (Figure 5.7). The carbon atom sometimes uses two of its bonds to link with the same atom, forming a *double bond;* notice the double bonds in the lower sets of molecules of Figure 5.7.

We refer to carbon molecules generically as **organic molecules.** The simplest organic molecules consist of carbon skeletons bonded only to hydrogen atoms; these simple organic molecules are often called *hydrocarbons* to reflect the fact that they contain only hydrogen and carbon. In more complex organic molecules, one or more carbon atoms are bonded to something besides hydrogen and other carbon atoms (Figure 5.8).

NON-CARBON-BASED LIFE When we consider the possibility of extraterrestrial life, it's natural to wonder whether it might be based on an element besides carbon. In truth, we cannot say for sure whether other elements would work. However, given the importance to life on Earth of carbon's ability to form four bonds at once, we might expect that any

*We have not yet identified every type of living organism on Earth, so it is still conceivable that we'll someday discover organisms right here on Earth (perhaps deep underground or in other isolated ecosystems) that use a different biochemistry and hence seem to have come from a separate origin of life. If so, it would greatly expand our understanding of biology, since we'd have more than one form of life to study up close in our laboratories.

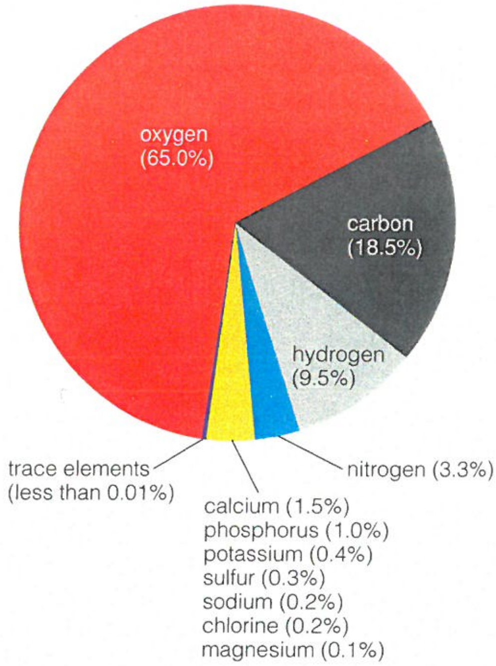


Figure 5.5

This pie chart shows the chemical composition of the human body by weight; this composition is fairly typical of all living matter on Earth. The trace elements include (in alphabetical order) boron, chromium, cobalt, copper, fluorine, iodine, iron, manganese, molybdenum, selenium, silicon, tin, vanadium, and zinc. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

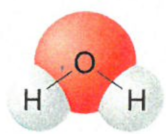


Figure 5.6

A water molecule has a single oxygen atom bonded to two hydrogen atoms. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

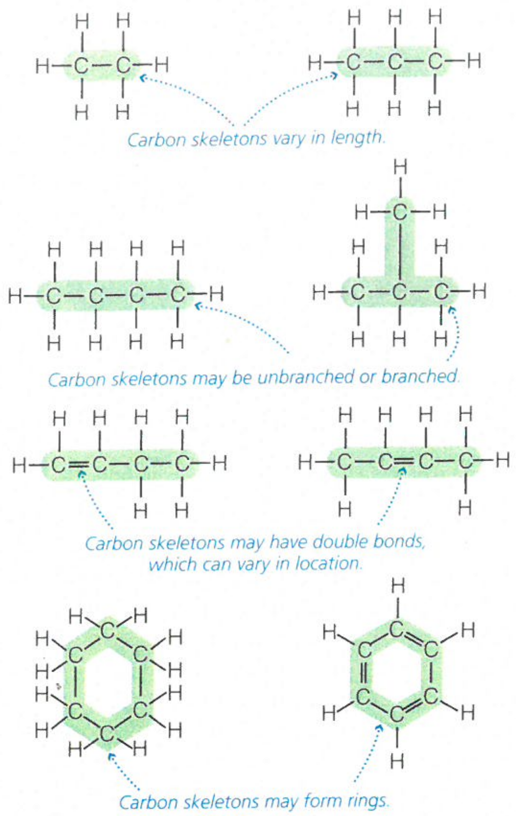


Figure 5.7

These diagrams represent several relatively simple hydrocarbons—organic molecules consisting of a carbon skeleton attached to hydrogen atoms. The carbon skeletons are highlighted in green. Each single line represents a single chemical bond; a double line represents a double bond. Note that every carbon atom has a total of four bonds (a double bond counts as two single bonds). (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

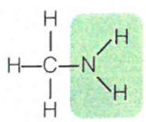


Figure 5.8

In a more complex organic molecule, at least one bond links a carbon atom to something besides hydrogen or another carbon atom. Here, one of the carbon atom's four bonds links it to an *amino group* (which consists of a nitrogen atom and two hydrogen atoms), highlighted in green. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

other elemental basis for life would have to have the same bonding capability. Among the elements common on Earth's surface—and likely to be common on other planets—silicon is the only element besides carbon that can have four bonds at once. As a result, science fiction writers have often speculated about finding silicon-based life on other worlds.

Unfortunately for science fiction, silicon has at least three strikes against it as a basis for life. First and most important, the bonds formed by silicon are significantly weaker than equivalent bonds formed by carbon. As a result, complex molecules based on silicon are more fragile than those based on carbon—probably too fragile to form the structural components of living cells. Second, unlike carbon, silicon does not normally form double bonds; instead, it forms only single bonds. This limits the range of chemical reactions that silicon-based molecules can engage in as well as the variety of molecular structures that can form. Third, carbon can be mobile in the environment in the form of gaseous carbon dioxide, but silicon dioxide is a solid (for example, quartz is made from silicon dioxide) that offers no similar mobility. Given the three strikes against silicon, most scientists consider it unlikely that life can be silicon-based. Moreover, observational evidence on Earth also argues against silicon: Silicon is about 1000 times as abundant as carbon in Earth's crust, so the fact that life here is carbon-based despite the greater abundance of silicon suggests that carbon will always win out over silicon as a basis for life.

A few other elements have also been suggested as possibilities for replacing carbon on other worlds, but most scientists believe carbon's natural advantages will still win out. We have found carbon-based (organic) molecules even in space (as identified in meteorites and interstellar clouds), suggesting that carbon chemistry is so easy and so common that even if life with another basis were possible, carbon-based life probably would arise first and then reproduce so successfully that it would crowd out the possibility of any other type of life. Nevertheless, we should not completely rule out the possibility of non-carbon-based life, and some scientists are therefore seeking to learn more about how we might recognize it, if it exists. As a recent report from the National Research Council stated, "Nothing would be more tragic in the ... exploration of space than to encounter alien life without recognizing it."

• What are the molecular components of cells?

All the major components of cells are made from complex organic molecules. Today, biologists know the precise chemical structure of a great many of these molecules, and this knowledge has enabled them to gain a deep understanding of the biochemistry of life. If you take a course in biology, you will learn about much of this biochemistry; here we focus only on generalities about the molecules of life. The large molecular components of cells fall into four main classes: *carbohydrates, lipids, proteins,* and *nucleic acids.* Let's briefly investigate the properties of each class that are most important to life.

CARBOHYDRATES You're probably familiar with **carbohydrates** as a source of food energy—the sugars and starches known to athletes and dieters as "carbs." In addition to providing energy to cells, carbohydrates make important cellular structures. For example, a carbohydrate called *cellulose* forms the fibers of cotton and linen and is the main constituent of wood. Life on other worlds would presumably need molecules to play these same energy-storing and structural roles, but we do not yet know whether such molecules would have to resemble carbohydrates on Earth or if they could be very different in their chemistry. As a result, we will have little more to say about carbohydrates in this book.

LIPIDS Like carbohydrates, **lipids** can store energy for cells. The types of lipids that store energy are more commonly known as *fats*. Thus, despite the bad reputation of fat, it is actually critical to living cells. Lipids also play a variety of other roles in cells on Earth, but from the standpoint of life in the universe, perhaps their most important role is as the major ingredients of cell membranes. That is, lipids form the barriers that make it possible for cells to exist. Moreover, as we'll discuss in more detail in Chapter 6, the membrane-forming role of lipids is thought to have played a critical role in the origin of life: Lipids can spontaneously form membranes in water and probably did so on the early Earth. Other organic molecules would have been trapped inside the space formed by the membranes, making what were in essence tiny chemical factories. These tiny chemical factories may have facilitated the chemical reactions that ultimately led to the origin of life.

PROTEINS: KEY EVIDENCE FOR A COMMON ANCESTOR OF LIFE The molecules called **proteins** are often described as the workhorses of cells, because they participate in such a vast array of functions. Some proteins serve as structural elements in cells. Others, called **enzymes,** are crucial to nearly all the important biochemical reactions that occur within cells—including the copying of genetic material (DNA)—because they serve as *catalysts* for these reactions. A **catalyst** is any substance (not necessarily a single molecule) that facilitates or accelerates a chemical reaction that would otherwise occur much more slowly; the catalyst itself is not changed by the process. Enzymes are catalysts because they greatly accelerate the reactions in which they are involved, even though they enter and leave the reactions essentially unchanged. Moreover, because an enzyme is left unchanged after it catalyzes a reaction, a single enzyme can catalyze a specific chemical reaction many times without needing to be rebuilt.

All proteins, whether they serve as enzymes or in other roles, are large molecules built from long chains of smaller molecules called **amino acids.** The "amino" in amino acids refers to the *amino group* that they all share—a nitrogen atom bonded to two hydrogen atoms and a carbon atom (see Figure 5.8); amino acids also always contain what is called a *carboxyl group* (COOH). Different types of amino acids are distinguished by the different sets of atoms also bonded to the central carbon.

The nature of the amino acid chains that make proteins in living organisms provides important evidence supporting the idea that all life on Earth shares a common ancestor. Biochemists have identified more than 70 different amino acids, but most life on Earth builds proteins from only 20 of them. (Two additional amino acids are known to be used in rare cases by particular microorganisms, and scientists suspect that other cases of rare amino acids may yet be discovered.) If life on Earth had more than one common ancestor, we might expect that different organisms would use different sets of amino acids, but they don't. Moreover, naturally occurring amino acids come in two slightly different forms, distinguished by their **handedness** (or *chirality*): The "left-handed" and "right-handed" versions are mirror images of each other (Figure 5.9). Amino acids found

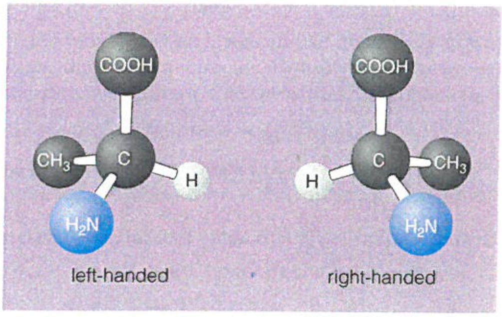


Figure 5.9

Any particular amino acid comes in two forms, distinguished by their *handedness*. These diagrams show the left- and right-handed versions of the amino acid *alanine*. Notice that the two versions are mirror images of each other.

in nonbiological circumstances generally consist of a mix of the left- and right-handed versions, but living cells use only the left-handed versions of amino acids to build proteins. Again, the fact that all life on Earth makes use of the same versions of amino acids suggests a common ancestor. Carbohydrates provide some similar evidence, as life on Earth uses mainly the right-handed versions of sugars.

Think About It Large impacts can blast meteorites into space, allowing rocks from one world to travel to another. As we'll discuss in Chapter 6, some scientists hypothesize that microscopic life might survive such impacts and thereby might have migrated between the inner worlds of our solar system. Suppose we discover life on Mars and we find that, while it also has proteins, it builds them from a different set of amino acids than does life on Earth, and they are all the right-handed versions. Would this support or contradict the hypothesis that life migrated between Earth and Mars? Explain.

NUCLEIC ACIDS Perhaps no cellular molecule is more famous than DNA, which is the basic hereditary material of all life on Earth. A second important nucleic acid, RNA (short for "*r*ibo*n*ucleic *a*cid"), helps carry out the instructions contained in DNA. Thus, the nucleic acids DNA and RNA are responsible for allowing cells to function according to precise, heritable instructions. Changing a cell's DNA changes the inherent nature of an organism; indeed, it is changes to DNA that allow species to evolve. We do not know whether other types of molecules could replace nucleic acids in life elsewhere, but it is difficult to imagine life existing in any form without a molecule or molecules to serve the hereditary functions of DNA and RNA. These molecules are so important that we'll devote Section 5.4 to discussing them in more detail.

• What are the major groupings of life on Earth?

Until just a couple decades ago, life was generally classified only by outward appearances. For thousands of years, these appearances suggested that life existed only in two basic forms: plants and animals. The first evidence of a different reality surfaced around the same time as the Copernican revolution. While Galileo turned his telescopes to the heavens, other scientists began to employ similar lens technology to study the microscopic world. The precise origin of the microscope is not known, but the first practical microscopes used for scientific study were built by the Dutch scientist Anton Van Leeuwenhoek (1632–1723; last name pronounced "LAY-ven-hook"). During decades of observations beginning around 1674, Leeuwenhoek discovered the world of microscopic life. He was the first to realize that drops of pond water are teeming with microorganisms—a discovery now repeated by almost every elementary school student. He also discovered bacteria and studied the microscopic structure of many plant and animal cells.

With hindsight, it may seem surprising that anyone could have thought that all microorganisms might just be tiny plants or animals, since we now know that microorganisms are far more genetically diverse than larger organisms. But that is exactly what happened. If you look at an old-enough biology textbook, you'll see that life was classified into two "kingdoms," the plants and the animals, and microbes were generally just stuck into one of those two. In the 1960s, biologists expanded the list to five kingdoms, with two (*protista* and *monera*) reserved for microorganisms; the third new addition was *fungi,* by then recognized to be different from plants. However, as our understanding of biochemistry improved during the ensuing decades, biologists began to consider whether life could be classified by its cell structure or biochemistry (including genetics), rather than by its outward appearance. Today, we know that classification by the biochemistry of cells gives us much deeper insights into the relationships among different living species than does classification by appearances alone.

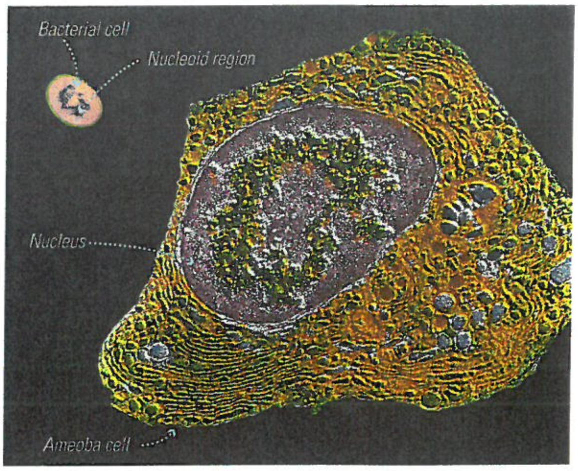


Figure 5.10

These microscopic photographs contrast a typical amoeba (a single-celled organism of domain eukarya) and a typical bacterial cell. Notice the very different sizes and cell structures; differences in biochemistry and genetics are even greater.

MICROSCOPIC LIFE Because we are more familiar with plants and animals than with microbes (meaning any single-celled organism), most people assume that microscopic life is a "minor" part of life on Earth. And because we tend to associate bacteria with disease, many people assume that microbes are generally harmful. Both assumptions are wrong.

Although we humans like to think of ourselves as the dominant form of life on Earth, measurements show that microbes are far more dominant in terms of mass and volume (see Cosmic Calculations 5.1). These microbes are remarkably diverse, varying substantially in size, cell structure, biochemistry, and genetics (Figure 5.10).

Moreover, most microbes are harmless to humans, and many are crucial to our survival. For example, bacteria in our intestines provide us with important vitamins, and bacteria living in our mouths prevent harmful fungi from growing there. Other microbes play crucial roles in cycling carbon and other vital chemical elements between organic matter and the soil and atmosphere; for example, microbes are responsible for decomposing dead plants and animals. Indeed, plant and animal life would be doomed if microbes somehow disappeared from Earth. In contrast, microbes could survive just fine without plants and animals, as they did during most of the history of life on Earth [Section 6.3].

Cosmic Calculations 5.1
The Dominant Form of Life on Earth

We can use estimation to show that microbes far outweigh human beings on Earth. We first estimate the total mass of the approximately 6 billion human beings on Earth. If an average person is 50 kilograms (110 pounds), the total human mass is about

$$6 \times 10^9 \text{ persons} \times 50 \frac{\text{kg}}{\text{person}} = 3 \times 10^{11} \text{ kg}$$

We next estimate the mass of microbes in the oceans. The density of microbes varies significantly with location and depth, but a rough average is *1 billion* (10^9) microbes per liter of water. Multiplying this value by the total volume of ocean water (a Web search reveals this to be about 1.4×10^9 km^3) gives us an estimate of the total number of microbes in the ocean:

$$\text{Total microbes} \approx \underbrace{10^9 \tfrac{\text{microbes}}{\text{liter}}}_{\text{density of microbes in ocean water}} \times \underbrace{(1.4 \times 10^9 \text{ km}^3)}_{\text{volume of ocean water}} \times \underbrace{\left(10^3 \tfrac{\text{m}}{\text{km}}\right)^3 \times \left(10^3 \tfrac{\text{liter}}{\text{m}^3}\right)}_{\text{convert from km}^3\text{ to liters}}$$

$$= 10^9 \tfrac{\text{microbes}}{\text{liter}} \times (1.4 \times 10^9 \text{ km}^3) \times \left(10^9 \tfrac{\text{m}^3}{\text{km}^3}\right) \times \left(10^3 \tfrac{\text{liter}}{\text{m}^3}\right)$$

$$= 1.4 \times 10^{30} \text{ microbes}$$

To find the total mass of microbes, we next need to know the typical microbe mass. A typical bacterium measures about 1 micrometer on a side, which means it has a volume of about 1 cubic micrometer. There are 1 million (10^6) micrometers per meter, so the volume of a bacterium is

$$1\ \mu\text{m}^3 \times \left(10^{-6} \tfrac{\text{m}}{\mu\text{m}}\right)^3 = 10^{-18} \text{ m}^3$$

Because life is made mostly of water, we can use the density of water (1000 kg/m^3) as the density of a microbe. Multiplying the microbe volume by the density, we estimate that the typical microbe mass is

$$10^{-18} \text{ m}^3 \times 10^3 \tfrac{\text{kg}}{\text{m}} = 10^{-15} \text{ kg}$$

We combine our results to find the total mass of microbes in the oceans:

$$\begin{aligned}\text{total mass of microbes} &\approx (\text{number of microbes}) \times (\text{mass per microbe}) \\ &= 1.4 \times 10^{30} \text{ microbes} \times 10^{-15} \tfrac{\text{kg}}{\text{microbe}} \\ &= 1.4 \times 10^{15} \text{ kg}\end{aligned}$$

We can compare to the mass of human beings by dividing:

$$\frac{\text{total mass of microbes}}{\text{total mass of humans}} \approx \frac{1.4 \times 10^{15} \text{ kg}}{3 \times 10^{11} \text{ kg}} \approx 5000$$

The total mass of microbes in the oceans is roughly 5000 times that of all humans combined.

THE THREE DOMAINS LIFE The classification of microbes long proved difficult. For decades during the twentieth century, biologists assumed that the presence or absence of a cell nucleus (such as the nucleus of the amoeba in Figure 5.10) represented a fundamental distinction. This visible distinction even led to different names for the two groups: Cells with nuclei were called *eukaryotes*, and those without were called *prokaryotes*. However, analysis of cellular biochemistry has shown that the latter are not a distinct group at all.

Today, biologists classify all life into three broad "superkingdoms," or **domains,** known as the **bacteria,** the **archaea,** and the **eukarya.** The domain eukarya includes not only thousands of known species of microbes, but also all complex plants, animals, and fungi. Cells of eukarya generally have cell nuclei, but this is no longer considered to be as fundamental as their biochemistry. The domains bacteria and archaea consist exclusively of microbes. While species within these two domains look similar under a microscope, study of their biochemistry—for example, the types of lipid structures in their cell membranes, the way in which they make cellular proteins, and most importantly their genetics—shows that they are not closely related. In fact, the archaea appear to be more closely related to eukarya than to bacteria.

THE TREE OF LIFE Biologists now routinely map relationships between species by comparing their DNA or the precise structures of molecules coded for by DNA. For reasons we'll discuss in more detail later, the greater the similarity in these molecules, the more closely the species are related. By studying these molecules in tens of thousands of species, both microbial and multicellular, biologists have mapped out what is usually called the **tree of life** (Figure 5.11).

Note that the tree of life gives us a very different picture of the diversity of life on Earth than the old idea of classifying life into "kingdoms" based on visible distinctions, and this new picture is thought to be far more accurate in depicting relationships among species. In particular, for our purposes in astrobiology, you should focus on three main features of the tree of life:

1. All large, multicellular organisms—meaning all plants, animals, and fungi—represent just three small branches of one domain (eukarya).
2. The true diversity of life on Earth is therefore found almost entirely within the microscopic realm. Biochemically and genetically, we humans (and all other animals) are much more closely related to mushrooms than most microbes are to one another.
3. The branch lengths in the tree of life represent the amount of genetic difference between species. Therefore, as we trace the branches back toward the "root," we are presumably looking back to species that split from the common ancestor at earlier times. The closer we get to the root, the closer we must be to finding an organism that resembles a common ancestor of all life on Earth.

Keep in mind that depictions of the tree of life are a work in progress. We have carefully studied only a tiny fraction of all the species that exist on Earth; indeed, we do not even know how many species there are, and we

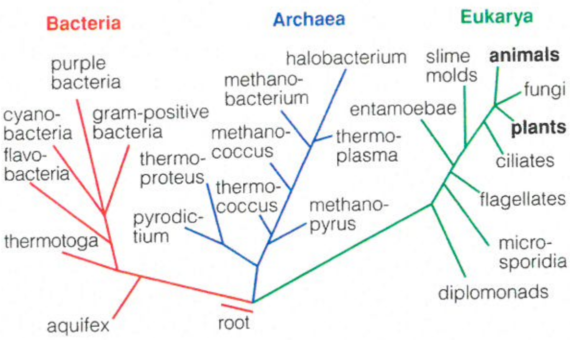


Figure 5.11

The tree of life has three major domains: bacteria, archaea, and eukarya; note that all plants and animals represent just two small branches of the domain eukarya. (Only a few of the many known branchings within each domain are shown in this diagram; it also remains possible that additional domains will be discovered.)

are only beginning to learn about many species that live in hard-to-reach environments such as the deep ocean and underground. We will certainly discover more branches within the three known domains, and it is even possible that we will discover entirely new domains in the future.

5.3 Metabolism: The Chemistry of Life

Why are cells so important to life on Earth? More to the point, is it possible that life elsewhere might exist without having a fundamental organizational unit like the cell? To answer these questions, we must understand the processes that take place inside living cells. These processes, which are all chemical in nature, make up what we call **metabolism.** More specifically, metabolism is a blanket term that refers to the many chemical reactions that occur in living organisms and are involved in providing energy or nutrients to cells.

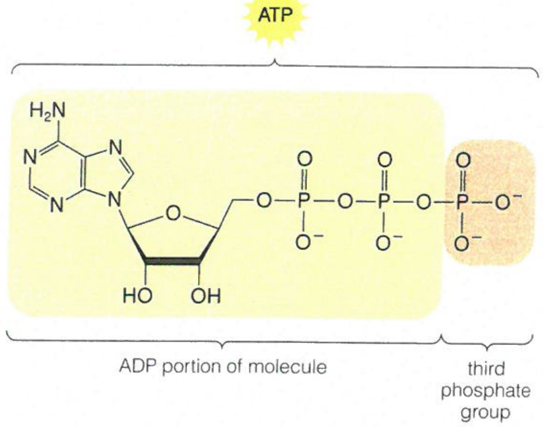
• What are the basic metabolic needs of life?

Most of the important chemical reactions that occur in cells share a common characteristic: Without the help provided by the cell itself, the reactions would occur too slowly to be useful for life. In this sense, a cell's primary purpose is to serve as a tiny chemical factory in which desired chemical reactions occur much more rapidly than they could otherwise, thereby making it possible to turn simple molecules into the great variety of complex organic molecules needed by living organisms. As is also the case in many factories, cellular work sometimes involves breaking down molecules as well as building them. Like any manufacturing process, this biochemical manufacturing process requires two basic things:

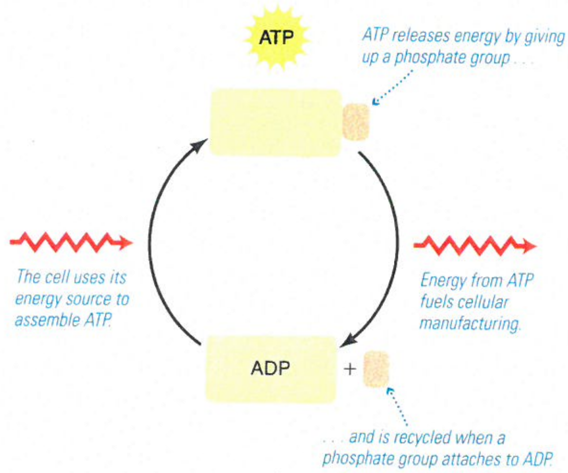
1. *A source of raw materials* with which to build new products. In the case of living cells, the key raw materials are molecules that provide the cell with carbon and other basic elements of life.
2. *A source of energy* to fuel the metabolic processes that break down old molecules and manufacture new ones.

Given the large variety of molecules involved in metabolic processes, you might think that cells would need an equally large variety of sources of raw materials and energy to survive. However, cells have the ability to build incredible variety from a limited set of starting materials. Part of this ability comes from the remarkable variety of enzymes in living cells. Each enzyme is specialized to catalyze particular chemical reactions needed in cellular manufacturing. The remarkable diversity of enzymes in living organisms today is a testament to the power of evolution. The instructions for enzyme creation are encoded in DNA and hence have been evolving for billions of years.

THE ROLE OF ATP Another reason why cells can produce so much variety from so little input is that, regardless of where they get their energy, all cells put the energy to work in the same basic way. Every living cell uses the same molecule, called **ATP** (short for "*a*denosine *t*ri*p*hosphate"), to store and release energy for nearly all its chemical manufacturing (Figure 5.12). Using ATP vastly simplifies the manufacturing process,



a **The molecular structure of ATP.** To understand the key parts of the structure, notice that the right side of the molecule shows three identical "phosphate groups," with the third one highlighted in pink. The portion of the molecule shown in yellow is ADP (adenosine diphosphate, because it has two of the phosphate groups), and the entire molecule, including the pink portion, is ATP (adenosine triphosphate, because it has three phosphate groups).



b **Cells recycle ATP.** The ATP molecule gives up energy when it splits into ADP (yellow) and a phosphate group (pink). Energy input puts the ATP molecule back together.

Figure 5.12

Every living cell on Earth uses the molecule ATP to store and release energy. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

because it means that a cell needs an outside energy source only for the purpose of producing ATP, rather than for producing the full variety of organic molecules in cells. Once ATP is produced, it can be used to provide energy for any cellular reaction. Moreover, the nature of ATP makes it completely recyclable. Each time a cell draws energy from a molecule of ATP, it leaves a closely related by-product, called ADP (short for "*a*denosine *di*phosphate"), that can be easily turned back into ATP.

The fact that all life on Earth uses the same molecule (ATP) for energy storage offers further evidence for a common origin of life. There's no known reason why other molecules could not fill the role of ATP. Thus, the fact that all living cells use ATP suggests that they all evolved from a common ancestor that made use of this remarkable molecule.

CARBON SOURCES AND ENERGY SOURCES Because carbon compounds are the primary raw materials needed for life, the needs of metabolism essentially come down to the need for a carbon source and an energy source. We humans, like all animals, meet both of these needs with food. The food we eat gets digested and carried in molecular form by our bloodstreams to individual cells. There, the cells make use of the molecules from our food sources. Some of the molecules are used as the carbon source for cellular manufacturing, while others undergo chemical reactions that release energy the cell can use to fuel its ATP cycle. Of course, not all organisms get their carbon and their energy by eating other organisms. Plants get energy from sunlight, and some microorganisms get energy from chemical reactions that take place inside rocks or in hot springs.

• How do we classify life by its metabolic sources?

Living cells on Earth get their carbon and energy from a surprisingly wide variety of sources. As we'll see, this wide variety makes life elsewhere seem more likely. For example, we already know of worlds within our own solar system, such as Mars and Europa, that may well have the necessary materials and energy source for metabolism, suggesting that life could at least in principle exist on those worlds.

Today, astrobiologists classify life into four major categories by its metabolic sources, summarized in Table 5.1. We can understand their rather long and technical names by looking first at their carbon sources and then at their energy sources.

TABLE 5.1 *Metabolic Classifications of Living Organisms**

Metabolic Classification	*Carbon Source*	*Energy Source*	*Examples*
photoautotroph	carbon dioxide	sunlight	plants, photosynthetic bacteria
chemoautotroph	carbon dioxide	inorganic chemicals (e.g., iron, sulfur, ammonia)	some bacteria and archaea, especially in extreme environments
photoheterotroph	organic compounds	sunlight	some bacteria and archaea
chemoheterotroph	organic compounds	organic compounds	animals, many microbes

*You may see similar tables that add a third classification category based on the source of electrons for energy transfer reactions: organisms are designated "organo-" if the electons come from an organic source and "litho-" if they come from an inorganic source. With this added distinction, the four classifications in the first column each branch into two (such as photolithoautotroph and photoorganoautotroph).

CARBON SOURCES: AUTOTROPHS AND HETEROTROPHS Cells need a source of carbon from which to build the skeletons of their organic molecules. In the broadest sense, cells can get their carbon in either of two ways:

1. Some cells get carbon by consuming preexisting organic compounds—that is, by eating. For example, we humans acquire carbon by eating plants or other animals. Any organism that gets its carbon by eating is called a **heterotroph;** the word comes from *hetero,* meaning "others," and *troph,* meaning "to feed." All animals are heterotrophs, as are many microscopic organisms.
2. Some cells get carbon directly from the environment by taking in carbon dioxide from the atmosphere or carbon dioxide dissolved in water. An organism that gets its carbon directly from the environment is called an **autotroph,** meaning "self-feeding." For example, trees and most other plants are autotrophs.

If you look at the first column of Table 5.1, you'll see that the first two entries are both autotrophs and the second two are both heterotrophs. However, in each case the entry carries a prefix of either *photo* (meaning "light") or *chemo* (meaning "chemicals"). These prefixes describe the energy source that goes with the carbon source of either eating (heterotroph) or taking in environmental carbon dioxide (autotroph).

ENERGY SOURCES: LIGHT OR CHEMICALS Broadly speaking, the energy that a living cell uses to make ATP can come from one of three sources (see Section 9.4 for more details about chemical energy for life):

1. Some cells get energy directly from sunlight, using the process we call *photosynthesis.* For example, plants acquire their energy from sunlight. Organisms that get energy from sunlight are given the prefix *photo.*
2. Some cells get energy from food; that is, they take chemical energy from organic compounds they've eaten and use it to make their own ATP. Since the energy comes from chemical reactions, these organisms get the prefix *chemo.*
3. Some cells get energy from *inorganic* chemicals—chemicals that do *not* contain carbon—in the environment. This type of energy source is different in character from organic food, and cells that get energy directly from the environment require neither sunlight nor other organisms to survive. However, because the energy still comes from chemical reactions, these organisms also get the prefix *chemo.*

THE FOUR METABOLIC CLASSIFICATIONS We can now put the carbon and energy sources together to understand the four metabolic classifications in Table 5.1. The first row of the table shows the **photoautotrophs,** which get their energy from sunlight (*photo*) and their carbon from carbon dioxide in the environment (making them autotrophs). This category therefore includes plants, as well as microorganisms that obtain their energy through photosynthesis.

The second row shows the **chemoautotrophs,** which obtain energy from chemical reactions (*chemo*) involving inorganic chemicals and carbon from environmental carbon dioxide (making them autotrophs).

These are in some ways the most amazing organisms, because they need neither organic food nor sunlight to survive. For example, the archaea known as *Sulfolobus* (a genus that includes many distinct species) live in volcanic hot springs and obtain energy from chemical reactions involving sulfur compounds. As is the case with *Sulfolobus*, chemoautotrophs are often found in environments where most other organisms could not survive. For much the same reason, they may also be the organisms most likely to be found on other worlds, since a wider range of conditions seems suitable to them than to other forms of life.

The third row shows the **photoheterotrophs,** which get energy from sunlight (*photo*) but get their carbon by consuming other organisms or the remains of such organisms (making them heterotrophs). This category is much rarer, but some bacteria and archaea do indeed get their carbon by eating organic compounds while making ATP with energy from sunlight. Examples include bacteria known as *Chloroflexus*, which obtain their carbon from other bacteria but their energy from photosynthesis. These organisms live in lakes, rivers, hot springs, and some aquatic environments very high in salt content.

The fourth row shows **chemoheterotrophs,** which get both their energy and their carbon from food. This category therefore includes us and all other animals, as well as many microorganisms. That is, we are chemoheterotrophs because we extract chemical energy (*chemo*) from food and carbon from eating (making us heterotrophs).

Think About It Classify each of the following into one of the four metabolic categories listed in Table 5.1: (a) an organism that gets its energy from chemicals near an undersea volcano and gets its carbon from carbon dioxide dissolved in water; (b) a tomato plant; (c) a fly.

METABOLISM, WATER, AND THE SEARCH FOR LIFE The four metabolic classifications are quite general, so they ought to apply equally well to life elsewhere as to life on Earth. Moreover, any type of complex metabolism requires the existence of some kind of structure that allows carbon and energy to come together to manufacture (and break down) the molecules needed for life. Thus, unless we are failing to imagine an entirely different potential mode of operation, it seems likely that all living organisms must have a fundamental structure that functions much like cells on Earth. This crucial observation means that we can search for life in the universe by searching for cells rather than having to search for a much broader variety of possible structures.

This leaves us with one final ingredient to consider in metabolism: liquid water. On Earth, water plays three key roles in metabolism. First, metabolism requires that organic chemicals be readily available for reactions. Liquid water makes this possible by allowing organic chemicals essentially to float within the cell (because the chemicals dissolve in water). Second, metabolism requires a means of transporting chemicals to and within cells, and of transporting waste products away; water is the medium of this transport. Third, water plays a role in many of the metabolic reactions within cells; for example, water molecules are necessary for the reactions that store and release energy in ATP.

All living cells on Earth depend on liquid water to play these three roles, and this dependence limits the conditions under which we find life on our planet: We find life only in places where it is neither too cold nor too hot for liquid water to exist. Indeed, while we've seen that life on Earth can use a variety of different carbon and energy sources, liquid water is one thing that no organism on Earth can survive without. (Some organisms can become dormant and grow or metabolize in the absence of liquid water, but they cannot survive permanently in such conditions.) Does this need for liquid water also apply to life on other worlds? Certainly, some kind of liquid seems necessary, but we'll save discussion of possibilities other than water for Chapter 7.

5.4 DNA and Heredity

In the previous two sections, we studied two key features of life on Earth that are likely to be crucial to life anywhere else as well: the structural units of cells and the metabolic processes that keep cells alive. A third feature that seems generally needed for all life is some means of storing information—that is, a set of "operating instructions" for the cell and a way of passing these instructions down through the generations. This information is what we generally call an organism's *heredity.*

All living things on Earth encode their hereditary information in the molecule known as DNA (although some viruses use RNA). That is, DNA holds the "operating instructions" for living organisms on Earth. DNA also allows organisms to reproduce, because it can be accurately copied. In this section, we will explore how DNA determines the nature of an organism and allows reproduction. We will also discuss how rare errors in the copying of DNA can lead to evolutionary adaptations, thus giving us the molecular-level understanding of natural selection that we first discussed in Section 5.1.

• How does the structure of DNA allow for its replication?

The molecular structure of DNA, a *double helix,* is one of the most familiar scientific icons of our time (Figure 5.13). A helix is a three-dimensional spiral, such as you would make by extending a Slinky toy; a double helix has two intertwined strands, each in the shape of a helix. The structure looks much like a zipper twisted into a spiral. The fabric edges of the zipper represent the "backbone" of the DNA molecule, while the zipper teeth that link the two strands represent molecular components called **DNA bases.** The chemical structure of the backbone is interesting and important in its own right, but it is the DNA bases that hold the key to heredity. Life on Earth makes use of only four DNA bases: adenine (abbreviated A), guanine (G), thymine (T), and cytosine (C).

The key to DNA's ability to be duplicated by cellular machinery lies in the way the four DNA bases pair up to link the two strands: T can pair up only with A, while C can pair up only with G. Figure 5.13 shows this pairing by representing the different bases with different shapes. For example, the shape of A, which is depicted as ending with an open triangle, fits only into the notch in T. Similarly, what is shown as the curved end of G fits only into the curved notch in C. These diagrams are only schematic representations—there aren't literally notches and curves on the DNA bases—but the real chemical bases work much the same way. Their actual shapes and sizes determine how they pair up.

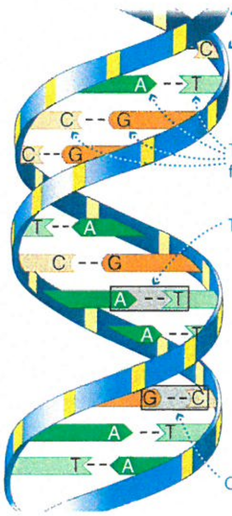


Figure 5.13

This diagram represents a DNA molecule, which looks much like a zipper twisted into a spiral. The important hereditary information is contained in the "teeth" linking the strands. These "teeth" are the DNA bases. Only four DNA bases are used, and they can link up between the two strands only in specific ways: T attaches only to A, and C attaches only to G. (The color coding is arbitrary and is used only to represent different types of chemical groups; in the backbone, blue and yellow represent sugar and phosphate groups, respectively.) (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

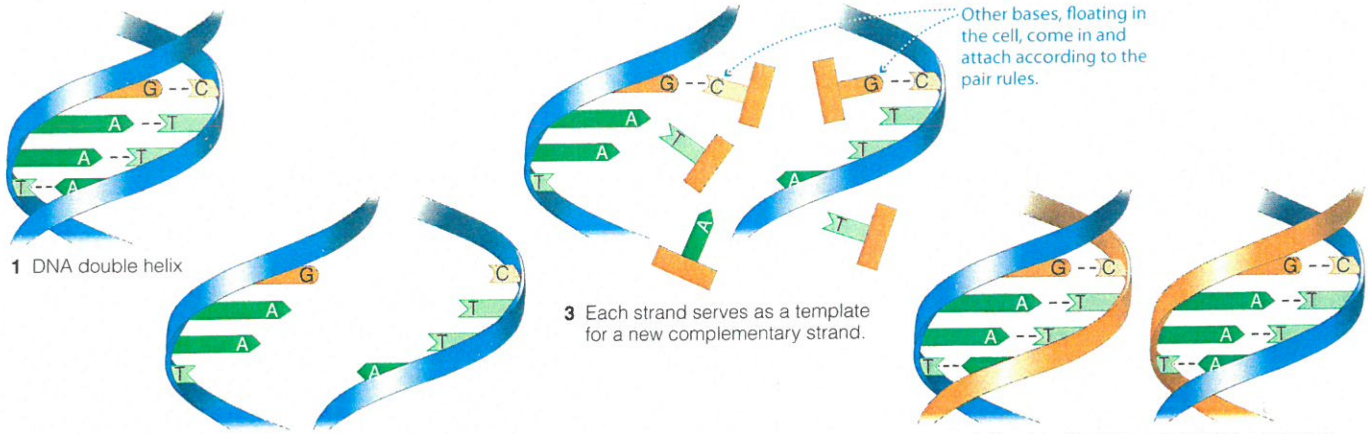


Figure 5.14

DNA replication. DNA copies itself by "unzipping" its two strands, each of which then serves as a template for making a new, complementary strand built in accord with the base pairing rules: A goes only with T, and C goes only with G. The end result is two identical copies of the original DNA molecule. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

The process by which DNA is copied, called **DNA replication,** is illustrated in Figure 5.14. Step 1 begins with the complete double helix. In Step 2, the two strands separate, "unzipping" the links between the paired bases. Step 3 shows how, once the strands have been "unzipped," each strand can serve as a template for making a new strand. Because the "teeth" of each new strand must link to the existing strands according to the base pairing rules—T goes only with A, and C goes only with G—each new strand will be *complementary* to an existing one. (By saying that two strands are complementary, we mean that, while they are not identical, they contain the same information because knowing the base sequence on one strand automatically tells us the base sequence on the other strand.) The end result, shown in Step 4, is two identical copies of the original DNA molecule. When a cell divides, one copy goes to each daughter cell. Because cell division is the key to passing down genetic material from one generation to the next, DNA replication explains the basis of heredity.

Although the DNA copying process is easy in principle, the actual mechanics are fairly complex. More than a dozen special enzymes are involved in the various steps, performing tasks such as unzipping the double helix, making sure the correct bases pair up, checking for and correcting any errors in the copying process, and rezipping the new DNA molecules. This complexity is one reason why errors sometimes occur in DNA replication; as we'll discuss shortly, these errors are crucial to evolution. The complexity of replication also makes it extremely unlikely that DNA could have been the original hereditary molecule for life on Earth. Instead, most biologists believe that DNA evolved from a simpler self-replicating molecule—probably a form of RNA—that carried hereditary information in the earliest living organisms [Section 6.2]. However DNA evolved, it has proved remarkably successful—it is now the hereditary material for every known organism on Earth. The basic copying process shown in Figure 5.14 explains how all life on our planet, from the smallest bacteria to humans, passes its genetic information from one generation to the next.

• How is heredity encoded in DNA?

Besides having the ability to be replicated, DNA also determines the structure and function of the cells within any living organism. In essence, the "operating instructions" for a living organism are contained in the precise arrangement of chemical bases (A, T, C, and G) in the organism's DNA. Today, biologists have technology that allows them to rapidly determine the sequence of bases in almost any strand of DNA. This technology has been used to determine the DNA sequences that code for many cell functions, as well as to determine the complete DNA sequences of many living organisms. For example, the Human Genome Project, completed in 2003, was a 13-year effort in which scientists ultimately determined the order of all three billion bases that make up the DNA of a human being. (In humans, this DNA is spread among the 46 *chromosomes* found in normal human cells.)

GENES AND GENOMES Within a large DNA molecule, isolated sequences of DNA bases represent the instructions for a variety of cell functions. For example, a particular sequence of bases may contain the instructions for building a protein, for building a piece of RNA, or for carrying out or regulating one of these building processes. The instructions representing any individual function—such as the instructions for building a single protein—make up what we call a **gene.** A gene is the basic functional unit of an organism's heredity—a single gene consists of a sequence of DNA bases (or RNA bases, in some viruses) that provides the instructions for a single cell function.

Interestingly, among plants, animals, and other eukarya, most of the DNA is *not* part of any gene; that is, much of the DNA does not appear to carry the instructions for any particular cell function. For example, this so-called **noncoding DNA** (sometimes called "junk DNA") makes up more than 95% of the total DNA in human beings, and similarly large fractions of the DNA of many other eukaryotes. Biologists suspect that most of this noncoding DNA represents evolutionary artifacts—pieces of DNA that may once have had functions in ancestral cells but that no longer are important, much like the way the appendix is an organ that no longer plays an important role in our bodies. However, recent discoveries suggest that at least some of the noncoding DNA may function in ways that are not yet fully understood.

The complete sequence of DNA bases in an organism, encompassing all of the organism's genes as well as all its noncoding DNA, is called the organism's **genome.** Figure 5.15 summarizes the relationship between DNA, genes, chromosomes, and the full genome.

Different organisms have genomes that vary significantly both in total length (number of bases) and in their numbers of genes. For example, some simple microbes have DNA that extends only a few hundred thousand bases and contains only a few hundred genes.* We humans have a genome that contains an estimated 20,000 to 25,000 genes among its sequence of some three billion DNA bases. Note that, genetically speaking, we are by no means the most complex organisms on Earth. Rice, for example, has about 37,000 genes, though it has a shorter total DNA sequence than humans. Other organisms have far more DNA than people. For example, the simple plant known as the "whisk fern" (*Psilotum nudum*) has more than 70 times as many bases in its genome as humans, though most of this extra DNA is probably noncoding.

*Many viruses are far simpler, with just a few thousand bases and a handful of genes. Mitochondria within eukaryotic cells, which are thought to have had free-living ancestors, are also much simpler than the simplest bacteria sequenced to date. For example, human mitochondria have fewer than 17,000 DNA base pairs, representing fewer than 40 genes.

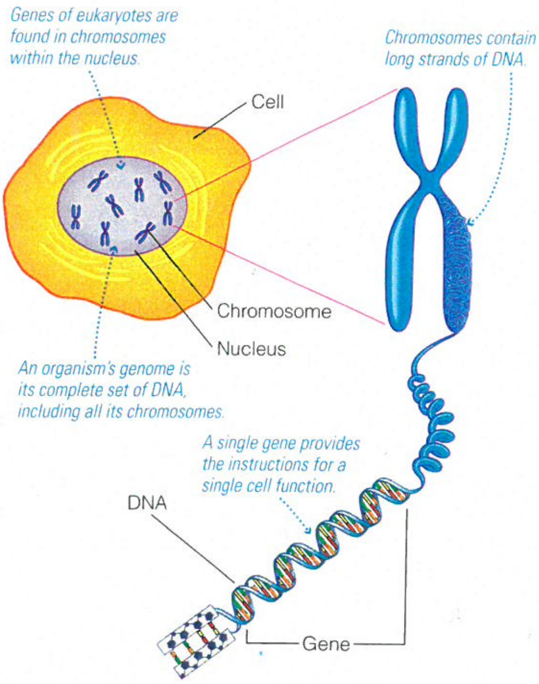


Figure 5.15

An organism's genome is its complete set of DNA. This artwork summarizes the relationship between DNA, genes, chromosomes, and the full genome in a eukaryotic cell. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

Every member of a particular species has the same basic genome. However, there is always some variation among individuals. For example, while all human beings have the same set of genes, the genes of different individuals may vary here or there in their precise sequence of DNA bases. These differences in the genes of individuals explain why we are not all identical, and they are also the source of the individual variation that underlies the theory of evolution (see Fact 2 on p. 157). Moreover, with a few exceptions, every cell in a living organism contains the same set of genes. Different cell types, such as muscle cells or brain cells, differ only because they *express*, or actually use, different portions of their full set of genes. Thus, the DNA found in almost any cell in any organism contains the complete instructions for building an organism of that species. This fact underlies the science of *cloning*, in which a single cell from a living organism is used to grow an entirely new organism with an identical set of genes.

THE GENETIC CODE A strand of DNA contains a long, unbroken sequence of DNA bases; for example, a particular sequence might contain the bases ACTCAGCTTCAACGG.... For a sequence like this to be useful as the instructions for a cell function, there must be a set of rules for how to "read" the sequence. These rules must specify how to break the long sequence into individual "words," as well as where to start reading and where to stop reading the words that represent the instructions for a single gene. The set of rules for reading DNA is called the **genetic code** (Figure 5.16). More specifically, genetic "words" consist of three DNA bases in a row. For the purpose of protein building, each word represents either a particular amino acid or a "start reading" or "stop reading" instruction.

Because the genetic words consist of three DNA bases in a row and there are four DNA bases to choose from (A, C, T, G), the total number of words in the genetic code is $4^3 = 4 \times 4 \times 4 = 64$; all 64 words are spelled out in Figure 5.16. Notice that this is significantly more than the number of amino acids used to make proteins, which is 20 for most organisms. Thus, the genetic code contains a fair amount of redundancy. For example, the genetic words ACC and ACA both represent the same amino acid. Moreover, a close examination of the genetic code offers a

Figure 5.16

The genetic code. This table shows how three-base-pair "words" of DNA code for particular amino acids or a start or stop instruction. For example, you can find the "word" CAG by looking along the left for C as the first base, along the top for A as the second base, and along the right for G as the third base; you'll then see that CAG codes for the amino acid glutamine. Notice that in most cases, the first two letters alone determine the amino acid; for example, if the first two letters are CT, the amino acid is always leucine regardless of the third letter. This suggests that the current genetic code evolved from an earlier version that used only two-letter "words" rather than three-letter "words."

second base

first base	T		C		A		G		third base
T	TTT	Phenylalanine	TCT	Serine	TAT	Tyrosine	TGT	Cysteine	T
	TTC		TCC		TAC		TGC		C
	TTA	Leucine	TCA		TAA	stop	TGA	stop	A
	TTG		TCG		TAG	stop	TGG	Tryptophan	G
C	CTT	Leucine	CCT	Proline	CAT	Histidine	CGT	Arginine	T
	CTC		CCC		CAC		CGC		C
	CTA		CCA		CAA	Glutamine	CGA		A
	CTG		CCG		CAG		CGG		G
A	ATT	Isoleucine	ACT	Threonine	AAT	Asparagine	AGT	Serine	T
	ATC		ACC		AAC		AGC		C
	ATA		ACA		AAA	Lysine	AGA	Arginine	A
	ATG	Met or start	ACG		AAG		AGG		G
G	GTT	Valine	GCT	Alanine	GAT	Aspartic acid	GGT	Glycine	T
	GTC		GCC		GAC		GGC		C
	GTA		GCA		GAA	Glutamic acid	GGA		A
	GTG		GCG		GAG		GGG		G

hint about the likely evolution of DNA: The codes for most amino acids really depend on just the first two bases in the three-base genetic words. For example, all four of the three-base words starting with AC (ACC, ACA, ACT, and ACG) code for the same amino acid (threonine). This suggests that the genetic code once depended only on two-base words rather than three-base words. Most biologists now believe that early life-forms used only a two-base language, which later evolved into the current three-base language of the genetic code.

Think About It Note that a two-base language would allow only $4 \times 4 = 16$ possible words—not enough for all the amino acids used by living organisms today. What does this imply about proteins in early life-forms? Explain.

Another important feature of the genetic code is that it is the same in nearly all living organisms on Earth. Only a few organisms show any variations at all on this code, and these variations are minor. (Variations in the genetic code are also found in mitochondria, structures within eukaryotic cells that contain their own DNA.) Nevertheless, the fact that some variations occur tells us that not all the specifics of the genetic code were inevitable. If we think of the genetic code as a language, the fact that nearly all organisms use the same genetic code is as if everyone on Earth spoke the same language, even though other languages are possible. This common language of the genetic code is further evidence for a common ancestor of all life on Earth.

THE ROLE OF RNA While the sequence of bases in a gene holds the instructions for its function, the actual implementation of these instructions is quite complex. As with DNA replication, many enzymes are involved in carrying out genetic instructions. In addition, the molecule RNA plays a particularly important role in these functions. A molecule of RNA is quite similar in structure to a *single* strand of DNA, except that it has a slightly different backbone and one of its four bases is different from one of the DNA bases. [RNA uses a base called *uracil* (U) in place of DNA's thymine (T).]

Several different types of RNA participate in carrying out genetic instructions in the cell. For example, in the process of building a protein, a molecule of *messenger* RNA (or mRNA) is first assembled along one strand of DNA, essentially transcribing the DNA instructions for use in another part of the cell. The messenger RNA then goes to a site in the cell known as a *ribosome*—made of *ribosomal* RNA (rRNA)—where amino acids are assembled into proteins. Assembling the proteins requires individual amino acids, which are collected from within the cell and brought to the ribosome by molecules of *transfer* RNA (tRNA). Working together, the different types of RNA attach the amino acids into the chains that make proteins. (This process is called *translation*, because it effectively *translates* the genetic instructions into an actual protein.) In recent years, biologists have learned that RNA can play many other vital roles in cells, but the roles we have discussed will be enough for our purposes in this book.

• How does life evolve?

One of the most remarkable aspects of our current knowledge of DNA is that it has allowed us to further confirm Darwin's theory of evolution by natural selection. In particular, while Darwin had to base his theory on the variation in populations that he could directly observe, we now know precisely how such variation occurs at the molecular level. The key to this knowledge lies in understanding how DNA molecules gradually change through time. Based on what we've already said about DNA replication and protein building, we can see how and why changes in DNA occur.

MUTATIONS: THE MOLECULAR BASIS OF EVOLUTION Despite its complexity, DNA replication proceeds with remarkable speed and accuracy. Some microbes can copy their complete genomes in a matter of minutes, and copying the complete three-billion-base sequence in human DNA takes a human cell only a few hours. In terms of accuracy, the copying process generally occurs with less than one error *per billion* bases copied. Nevertheless, errors sometimes occur. For example, the wrong base may get attached in a base pair, such as linking C to A rather than to G. In other cases, an extra base may be inserted into a gene, a base may be deleted, or an entire sequence of bases might be duplicated or eliminated. Absorption of ultraviolet light or nuclear radiation or the action of certain chemicals (carcinogens) can also cause mistakes to occur. Any change in the base sequence of an organism's DNA is called a **mutation.**

Mutations can affect proteins in a variety of ways. Some mutations have no effect at all. For example, suppose a mutation causes the genetic word ACC to change to ACA in a gene that makes a protein. Because both of these words code for the same amino acid (threonine; see Figure 5.16), this mutation will not change the protein made by the gene. Other single-base mutations—such as changing ACC to CCC—will change a single amino acid in a protein. In some cases, such a change will alter a protein only slightly, hardly affecting its functionality. But in other cases, the change can be much more dramatic. For example, the cause of sickle-cell disease (Figure 5.17), which kills some 100,000 people each year worldwide, can be traced to a single mutation in the gene that makes hemoglobin, in which the base A changed to the base T in just one place within the gene.* Mutations that add or delete a base within a gene tend to have the most dramatic effects on protein structure. The reason is that the genetic code has no "punctuation" or spacing between words; instead of saying something like "the fat cat ate the rat," for example, it says "thefatcatatetherat." Thus, if a letter (base) is added to or deleted from such a sequence, the result will be nonsense from that point on. For example, inserting an "a" so that the sequence becomes "the*a*fatcatatetherat" would cause it to be read as "the *a*fa tca tat eth era t."

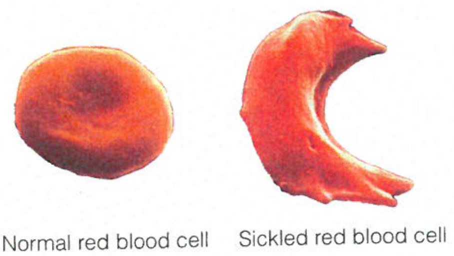


Figure 5.17

These microscopic views contrast a normal human red blood cell with a blood cell found in patients with sickle-cell disease. The sickle shape makes it easier for the blood cells to clog tiny blood vessels, which can lead to debilitating disease. Sickle-cell disease occurs in people whose gene for hemoglobin differs from the "normal" gene in just a single DNA base.

Mutations that change proteins are often lethal, because the cell may not be able to survive without the correctly structured protein. However, if the cell survives, the mutation will be copied every time its DNA is replicated. In that case, the mutation represents a permanent change in the cell's hereditary information. If the cell happens to be one that gets passed to the organism's offspring—as is always the case for single-celled organisms and can be the case for animals if the mutation occurs in an egg or sperm cell—the offspring will have a gene that differs from that of the parent. It is this process of mutation that leads to variation among

*Humans have two copies of each gene, and sickle-cell disease generally occurs only in people who have the sickle-cell mutation in both copies of the gene. From an evolutionary standpoint, this mutation remains prevalent in the population because it actually confers an advantage—malaria resistance—to people with only one copy of the mutated gene.

individuals in a species. Each of us differs slightly from all other humans because we each possess a unique set of genes with slightly different base sequences.

Think About It Ultraviolet radiation from the Sun can cause mutations in the DNA of skin cells. Based on what you've learned, explain why this is potentially dangerous (and, indeed, is the cause of skin cancer). How would sunscreen help prevent such mutations?

Mutations therefore provide the basis for evolution. Given that each individual of a species possesses slightly different genes, it is inevitable that some genes will provide advantageous adaptations to the environment. As we discussed in Section 5.1, the combination of individual variation and population pressure leads to natural selection, in which the advantageous adaptations will preferentially be passed down through the generations. Thus, what was once a random mutation in a single individual can eventually become the "normal" version of the gene for an entire species. In this way, species evolve through time. Notice that, while we often associate the word *mutation* with harm, evolution actually proceeds through the occasional beneficial mutation. Although such beneficial mutations may be relatively rare compared to other mutations, natural selection allows these beneficial mutations to propagate preferentially, so tremendous changes can accrue over time.

Evolution sometimes occurs in an even more dramatic way: In some cases, organisms can transfer entire genes to other organisms, a process called *lateral gene transfer.* This process is one of the primary ways that bacteria gain resistance to antibiotics. We humans have also learned to use this process for our benefit through what we call *genetic engineering,* in which we take a gene from one organism and insert it into another. For example, genetic engineering has allowed us to produce human insulin for diabetic patients: The human gene for insulin is inserted into bacteria, and these bacteria produce insulin that can be extracted and used as medicine. Lateral gene transfer can change a species more rapidly than individual mutations, but mutations are still the underlying basis, since they created the genes in the first place.

DNA AND LIFE ON OTHER WORLDS It is difficult to imagine life that does not have heredity, because it seems crucial for any form of life to have some means of storing its operating instructions and passing them on to its offspring. We've seen that DNA is the carrier of heredity for all life on Earth, though as we'll discuss in Chapter 6, we have good reason to believe that very early life on Earth used RNA for this role. Should we expect DNA or RNA to also be the heredity molecule for life elsewhere? We do not yet know whether other, quite different molecules might be able to carry hereditary information in the same way as DNA. However, it seems a near certainty that any form of life anywhere else will have some molecule that plays the same functional role that DNA plays on Earth.

5.5 Life at the Extreme

We've discussed all the fundamental characteristics of life on Earth: the basic structure of cells, the metabolism of cells, and the means by which cells store and pass on their heredity. We've also discussed why these characteristics seem likely to be shared, at least in a general sense, by any life

Figure 5.18

This photograph shows a black smoker—a volcanic vent on the ocean floor that spews out extremely hot, mineral-rich water. Organisms like *P. fumarii* and Strain 121 survive here in water above the normal boiling temperature.

we find elsewhere. In essence, our bottom-line conclusion is that life elsewhere ought to share a lot of common features with life on Earth. But don't be tempted to think this means that life elsewhere will look like us—that is, like humans or any other animals. In fact, most life on Earth does not look much like "us." We've already noted that microbes are far more common than multicellular eukarya. Perhaps even more startling, in recent decades biologists have discovered that life can survive in an astonishing variety of environments that would be lethal to humans.

• What kinds of conditions can life survive?

Deep on the ocean floor are places where volcanic activity releases hot water and rock into the surrounding ocean. Minerals and other dissolved chemicals can cause the water to turn black, which is why some of the vents and their plumes of hot water are called *black smokers* (Figure 5.18). The water coming out of such vents can be heated to temperatures above 350°C (660°F), far above the normal boiling point of 100°C (212°F). However, the ocean pressure at these depths is so great that the water remains liquid despite its high temperature.

If you took any "ordinary" organism and placed it in the extremely hot water near a volcanic vent, it would die quickly because the high temperature would cause many of its critical cell structures to fall apart. Yet in recent decades scientists have discovered life—mostly microbes of the domain archaea*—thriving in the extremely hot water around black

*Many known species of archaea live in extreme environments, but extreme conditions are *not* a general feature of domain archaea. Indeed, some of the most common organisms in "ordinary" environments on Earth are archaea. For example, some 20–50% of the living cells in cool ocean water typically represent various species of archaea.

MOVIE MADNESS
WAR OF THE WORLDS

In 1898, when British novelist H. G. Wells wrote *War of the Worlds,* some astronomers were claiming that long, linear features could be seen criss-crossing the surface of Mars (see Chapter 8). They proposed that intelligent beings, stuck on a dying, drying planet, were lacing their landscape with irrigation canals.

It occurred to Wells that such thirsty Martians might choose to stop all the civil engineering, abandon their withered world, and invade Earth—a planet awash in water. He penned a classic alien invasion story that has since been reworked for radio, television, and two big-budget movies.

Today most people know that Mars is not home to a vast, canal-crazed society, so when director Steven Spielberg re-made *War of the Worlds* in 2005, he studiously avoided mentioning the Red Planet. The aliens in his film just come from *somewhere*. They look vaguely feline and definitely unattractive, and arrive in lightning bolts, a mode of transport that has not yet caught the attention of NASA.

As these bolts reach Earth, they punch right through the pavement to some previously buried military machinery. Despite being mothballed for a million years, these alien tanks-on-legs fire right up. It's hard to imagine anyone using such old weapons: Would today's Air Force be happy to mount an invasion with Neolithic stone axes? Nonetheless, the aliens and their machines quickly emerge and proceed to stomp across the landscape, happily zapping humanity en route. As usual in such movies, our own military wastes its time and a lot of ordnance in a vain effort to discourage them. One character has the bad form to note the obvious: "This is not a war; this is an extermination."

With only a few minutes of film time to go, it's looking bad for *Homo sapiens*, as cities get trampled and citizens get sucked for blood. (Perhaps hemoglobin is a delicacy on these aliens' world?) But then ... a miracle occurs. The invaders get sick and keel over—done in not by us, but by earthly microbes. They have no immunity to our bacteria.

Frankly, it's a bit of a stretch to assume that alien biochemistry would be so similar to ours that the invaders would fall victim to terrestrial diseases. But the truly ironic thing about *War of the Worlds* is the idea that Martians (as they were identified in the original story) would invade us and be vanquished by microbes when—as we'll see later in this book—if there are any real Martians, they probably *are* microbes!

smokers and other vents. For example, an organism called *Pyrolobus fumarii*, which was actually discovered *in* the walls of a black smoker (its name means "fire lobe of the chimney"), can grow in water heated to as high as 113°C (235°F). And in 2003, researchers discovered another species of archaea living near volcanic vents that can grow in even hotter water. Nicknamed "Strain 121" (also called *Geogemma barossli*) because it can grow in water as hot as 121°C (250°F), it can also survive in the lab for up to 2 hours at temperatures of 130°C (266°F). Both *P. fumarii* and Strain 121 are chemoautotrophs that get their carbon from dissolved carbon dioxide and their energy from inorganic chemical reactions that occur in the hot water. Similar organisms thrive in hot springs on Earth's surface, such as in the springs around Yellowstone National Park (Figure 5.19).

Figure 5.19

A hot spring in Yellowstone National Park; to judge its size, notice the walkway winding along the lower right. The different colors in the water are from different bacteria that survive in water of different temperatures.

Organisms that survive in extremely hot water are sometimes called *thermophiles*, meaning "lovers of heat" (the suffix *phile* means "lover"), or, in the case of those living at the highest temperatures, *hyperthermophiles*. More generally, organisms that survive in extreme environments of any kind are called **extremophiles,** or "lovers of the extreme." Extremophiles are quite varied, though most of them are members of the domain bacteria or archaea. Some can live in "normal" as well as extreme conditions, while others can survive only in the extreme conditions. For example, many hyperthermophiles die when brought to "normal" temperatures because their enzymes have evolved to function only at the high temperatures in which they live. Many extremophiles are anaerobic (meaning they live without oxygen), and they are poisoned by the oxygen on which our own lives depend.

Hot environments are not the only extreme conditions favored by some organisms. The dry valleys of Antarctica receive so little rain or snowfall that they are among the driest deserts on Earth, and temperatures in these valleys rarely rise above freezing (Figure 5.20). Nevertheless, there is life in the dry valleys living *inside* rocks. We often think of rocks as solid, but most rocks are composed of individual mineral grains packed together, leaving small spaces between the grains. Even in the dry valleys, these spaces within the rocks occasionally contain water from the rare rain- or snowfall. Sunlight can penetrate up to a few millimeters into the rock before being completely absorbed, so the layers just below the rock's surface can have temperatures slightly above freezing despite the freezing temperatures around them. Amazingly, there are microbes that survive in these tiny pockets of liquid water inside rocks in freezing cold valleys.

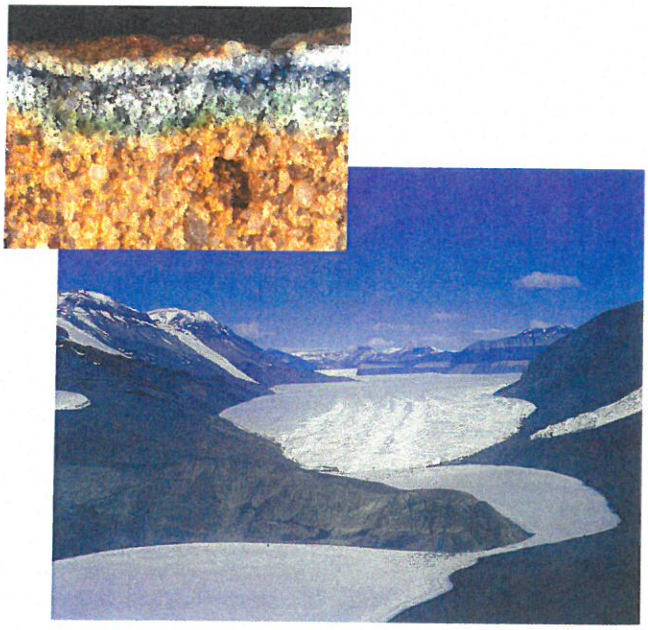


Figure 5.20

The main photo shows a cold, dry valley in Antarctica. These valleys are among the driest deserts on Earth (the ice is runoff from surrounding regions), yet they are still home to life. The inset shows a slice of rock (about 1.8 centimeters across) from a dry valley. The colored zones contain microbes that live inside the rock in the airspaces between tiny mineral grains. The organisms are dormant and frozen for most of the year, but can grow during the approximately 500 hours per year when sunlight warms the rock above the freezing point.

Other extremophiles live in conditions far too cold, acidic, alkaline, or salty for "ordinary" life to survive, and some may offer examples of the types of organisms we might find on other worlds. For example, there are some species that can survive at temperatures as low as −20°C (−4°F) as long as even a thin film of liquid water is available. (These cold-loving organisms are called *psychrophiles*, essentially the opposite of *thermophiles*.) Some microbes can even survive high doses of radiation. A bacterial species known as *Deinococcus radiodurans* can survive radiation more than 1000 times that which would be lethal to humans and other animals. These remarkable organisms actually thrive in radioactive waste dumps! They could survive the radiation exposure on a world without ozone and even in space, and they can survive extremely dry conditions as well.

One particular group of extremophiles is of special interest for its possible relevance to life on Mars. Microbes called *endoliths* (meaning "within rocks") can live several kilometers below the surface of Earth in water

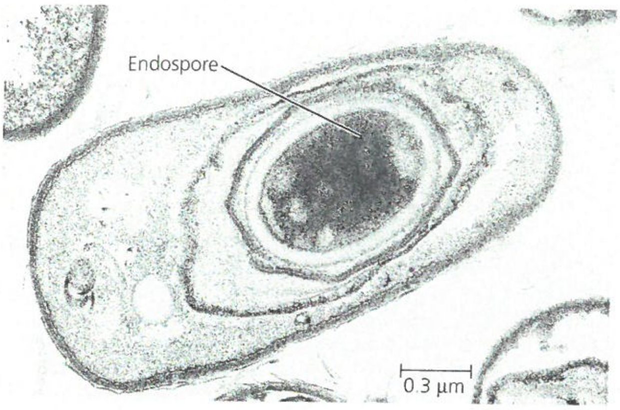


Figure 5.21

This microscopic photo shows an endospore created by the bacterium *Bacillus anthracis*. There are actually two cells here, one inside the other. The outer cell produced the specialized inner cell, which is the endospore. The endospore has a thick, protective coat. Its interior is dehydrated, and no metabolism occurs. Under harsh conditions, the outer cell may disintegrate, but the endospore can survive. When the environment becomes more hospitable, the endospore absorbs water and resumes growth.

that fills the pores within rock. One community of endoliths consists of bacteria living deep beneath the surface of Oregon and Washington in a rock formation known as the Columbia River Basalt; others have been found living in rock as far as 3 kilometers underground. These organisms are chemoautotrophs that get their energy for metabolism from chemical reactions between the water and the surrounding rock, and they get their nutrients from chemicals within the rock itself and from carbon dioxide that has filtered down from the surface. Although these microbes clearly share the same common ancestors as the rest of terrestrial life, they tell us something significant about life's ability to survive in remarkably diverse environments. In particular, the subsurface environment in which they live almost certainly exists in similar form on other planets, such as Mars, even when the surface may be too cold for liquid water. Moreover, endoliths may be quite common. No one knows exactly how many of them exist here on Earth, but some estimates suggest that the total mass of subsurface organisms living in rock may exceed that of all the life on Earth's surface.

Another amazing adaptation to extreme conditions is found in **endospores**—special "resting" cells produced by some bacteria (Figure 5.21). Endospores allow the organisms that create them to become dormant, neither growing nor dying in extremely inhospitable conditions. (The nondormant organisms are not necessarily extremophiles; some live under more "normal" conditions.) For example, endospores of the bacterium *Bacillus anthracis*, which causes the deadly disease anthrax, can survive a complete lack of water, extreme heat or cold, and most poisons. Some endospores can survive even in the vacuum of space, which is why planetary scientists worry that our interplanetary spacecraft could potentially contaminate other worlds with life from Earth. Moreover, some endospores can remain dormant for centuries—and perhaps even longer—raising the possibility that life could survive journeys aboard meteorites that are blasted off one planet and land on another [Section 8.4].

• Are extremophiles really extreme?

From our human point of view, the environments in which extremophiles survive truly are extreme. But if an extremophile could think, it would probably claim that its environment is quite normal and that ours is the one that is extreme. So who's right, humans or the extremophiles?

In some sense, it's all just relative. Any species would naturally consider its own environment to be normal and others to be extreme. A more important question we might ask is which environment is more common. Surprisingly, if we look at the history of Earth, so-called extreme environments have been much more common than an environment suitable for humans. Earth's atmosphere may have contained oxygen at a level suitable for human life for only the past few hundred million years, or about 10% of Earth's history [Section 6.3]. Indeed, for the first couple of billion years after life first arose on Earth, extremophiles were the only organisms that could survive. Even today, it's an open question whether extremophiles are more or less common than organisms that live in conditions favorable to humans. All in all, extreme life appears to be much more the norm than is life that lives in an environment suitable to humans.

The study of extremophiles has several important implications for the search for extraterrestrial life, but two are particularly important.

First, the fact that extremophiles apparently evolved earlier than other forms of life [Section 6.1] suggests that we should begin the search for life elsewhere by searching for similar extreme organisms. Second, the fact that extremophiles can survive such a broad range of conditions suggests that life may be possible in many more places than we would have guessed only a few decades ago: Any world containing an environment in which some type of extremophile might survive becomes a good candidate for the search for life.

THE PROCESS OF SCIENCE IN ACTION

5.6 Evolution as Science

In this chapter and throughout this book, we treat evolution as an established fact, a position consistent with official statements by virtually every scientific society, including the National Academy of Sciences, the American Association for the Advancement of Science, the National Association of Biology Teachers, and the American Astronomical Society. However, if you live in the United States, you've almost certainly heard about public battles in which the scientific idea of evolution is portrayed as being controversial. How can an idea so well accepted in science be considered so differently by many among the general public? The answer lies in differences between the way science works and the way that people often seek knowledge in their daily lives, and especially in the difference between the evidence-based approach of science and the faith-based approach of religion. Once this difference is understood, much of the supposed conflict between science and religion is not an issue, which explains why the vast majority of religious denominations see no inherent conflict between their faiths and the science of evolution. For this chapter's case study in the process of science, we'll explore why most scientists and most theologians agree that evolution and faith can coexist without difficulty.

• Is evolution a fact or a theory?

By this point in the book, you should already recognize that the question of whether evolution is a fact or a theory offers a false choice, much like asking whether gravity is a fact or a theory [Section 2.4]. Gravity is a fact in that objects really do fall down and planets really do orbit the Sun, but we use the *theory* of gravity to explain exactly how and why these things occur. The theory of gravity is not presumed to be perfect and indeed has at least one known flaw (its inconsistency with quantum mechanics on very small scales). Moreover, Newton's original theory of gravity is now considered only an approximation to Einstein's improved theory of gravity, which itself will presumably be found to be an approximation to a more complete theory that has not yet been discovered.

The same idea holds for evolution. Nearly all scientists consider evolution to be a fact, because both the geological record and observations of modern species make clear that living organisms really do change with time. We use the *theory* of evolution to explain how and why these changes occur. For example, we use the theory of evolution to understand the changes in species recorded in the geological record, the genetic relationships among modern species, and the way that bacteria can rapidly acquire resistance to antibiotics.

The theory of evolution clearly explains the major features of life on Earth, but scientists still debate the details of the theory. For example, there is considerable debate about the rate at which evolution proceeds: Some scientists suspect that evolution is "punctuated" with periods of rapid change followed by long periods in which species remain quite stable, while others suspect that evolution proceeds at a steadier pace. This debate can be quite heated between individual scientists, but it does not change the overall idea that life evolves, and it will eventually be settled by additional evidence. Similarly, scientists often debate the precise relationships among species, especially those that are extinct. For example, we do not yet have enough evidence to put together a complete evolutionary tree for relationships among all dinosaur species, and the relationship between extinct dinosaurs and modern birds is not yet fully understood.

We can draw an analogy between Darwin's original theory of evolution by natural selection and Newton's original theory of gravity: Just as Newton's theory captured the main features of gravity but proved to be incomplete, Darwin's theory clearly captures the main features of evolution but is not complete. Moreover, like Newton's theory, Darwin's also has been modified and improved with time. Just as Einstein's general theory of relativity allowed us to understand gravity in more realms than Newton's original theory (by refining it, not refuting it), so does our modern understanding of DNA and mutations allow us to understand biological changes and relationships beyond those that Darwin was able to understand or was even aware of. And like the theory of gravity, the theory of evolution remains a work in progress. We expect to learn more about evolution as we continue to study relationships among species, how DNA works (especially the noncoding regions), and the biochemistry of life. Perhaps someday we'll even be able to broaden the theory through the study of *comparative evolution*, in which we'll explore the similarities and differences among living organisms on multiple worlds.

Does all this mean that you need to *believe* that evolution really occurred? From the standpoint of learning science, what counts is *understanding* evolution; belief is up to you. Remember, all the evidence in the world can never prove any scientific theory true beyond all doubt [Section 2.3]. Even if we had a complete geological record, with precise dating of every species that ever lived, you could still choose to believe, for example, that the fossils had been placed there intact at some single moment in the past, rather than having been deposited as the evidence suggests. All we can say from a scientific viewpoint is that a tremendous wealth of evidence points to the idea that life on Earth has evolved through time, that these evolutionary changes have been driven by natural selection, and that natural selection occurs on a molecular level as genes are modified through mutations of DNA.

• Are there scientific alternatives to evolution?

In recent years, the public controversy over evolution has centered largely around the question of whether it should be the only idea about our origins taught in science classes or whether it should be taught alongside other, competing ideas. Other ideas certainly offer different visions of how we came to exist; for example, the idea that God created Earth and the universe a mere 6000 years ago is obviously quite different from the idea that life has evolved gradually over the past 4 billion years. The question is whether this idea or other competing ideas qualify as science.

The best way to determine whether any alternatives to evolution qualify is to consider them against the hallmarks of science that we discussed in Chapter 2. Let's start by showing that the theory of evolution *does* satisfy the standards of science. The first hallmark states that science seeks explanations for observed phenomena that rely solely on natural causes. The theory of evolution clearly does this, as it explains the geological record and observed relationships among species through the mechanism of natural selection and other natural causes.

The second hallmark states that science progresses through the creation and testing of models. Our understanding of evolution has indeed progressed in this way. The idea of evolution won out over Aristotle's competing idea of species that never changed. As the fact of evolutionary change gained acceptance, the first model proposed to explain these changes came from Lamarck (see Section 5.1); his model was later discarded because Darwin's alternative model explained the observations so much more successfully. Our current, molecular model of evolution is a refinement of Darwin's original model, and we can expect further refinements to the theory in the future as continued study turns up new evidence.

The theory of evolution also satisfies the third hallmark, which states that a scientific model must make testable predictions that would lead us to revise or abandon the model if the predictions did not agree with observations. Our modern, molecular theory of evolution clearly qualifies. For example, it predicts that diseases can and will evolve in response to medicines designed to combat them, a prediction borne out in the rapid way that many diseases acquire drug resistance. It also predicts that genetically similar species should respond to medicines in similar ways, a prediction confirmed by the fact that we can test many medicines in other primates and they do indeed have effects similar to those they have in humans. The theory of evolution also provides a road map that we can use to modify organisms through genetic engineering; in this sense, every genetically engineered grain of rice or kernel of corn represents a success of the predictive abilities of the theory of evolution.

In fact, even Darwin's original theory made testable predictions. For natural selection to be possible, living organisms must have some way of passing on their heritable traits from parent to offspring. So although Darwin did not predict the existence of DNA per se, his theory clearly predicted that some type of mechanism had to exist to carry the hereditary information. Similarly, now that we know about DNA and the genetic code, the theory of evolution predicts that closely related species should be genetically similar, a prediction that has been confirmed in just the past few years by genome sequencing. For example, in the ordering of their base sequences, the DNA of humans and chimpanzees is 98.5% identical. If we were not closely related to chimpanzees, we would not expect such similar genomes.

Now that we have established that evolution qualifies as science, we next turn to the question of whether any of the alternative models that have been suggested for inclusion in the classroom might also qualify as science. Since the time that Darwin first published his theory, the main alternatives have been religious ideas about creation. Here, we run into an immediate problem: There are so many different religious ideas about creation that we can't even define the potential alternatives clearly. For example, many Native American religious beliefs speak of creation in terms that bear little resemblance to the Judeo-Christian tradition found in Genesis. Even among people who claim a literal belief in the Bible, there are differences in interpretation about creation. Some biblical literalists argue that the creation must have occurred in just 6 days, as the first chapter of Genesis seems to say, while others suggest that the term "day" in Genesis does not necessarily mean 24 hours and therefore that the story in Genesis is compatible with a much older Earth and with evolution.

Nevertheless, a few groups have tried to claim that scientific evidence supports some alternative to evolution. In the 1980s, an idea called "creation science" emerged, and its proponents tried to find scientific evidence to support the idea that Earth was created a mere 6000 years ago. However, to support this "young Earth" view, they not only had to reject evolution but also had to reject the tremendous weight of evidence that supports an old Earth and an old universe—evidence based on such things as radiometric dating of rocks, astronomical measurements of distances to other stars and galaxies (since their light has obviously had time to reach us), and even tree ring data that go back more than 6000 years. For all this evidence to be wrong, we would have to have fundamental errors in our basic understanding of the laws of nature, an idea that seems implausible, given the many successes of modern physics and chemistry.

More recently, some people have advanced an idea called "intelligent design," or ID; this idea holds that living organisms are too complex to be explained by natural selection, and so must have been designed by some transcendent entity or power. For example, proponents of this idea point to features of the human eye as suggesting design rather than natural processes, and some believe they see evidence of "digital code" in the arrangement of the bases in the genomes of living organisms.

For the vast majority of scientists, the primary problem with these claims of intelligent design is that they do not seem to stand up to scientific scrutiny. The features that the ID proponents cite as evidence for design are to most scientists well explained by natural selection. Nevertheless, good scientists will always allow the possibility that evidence of design might someday be found. Moreover, even if no such evidence is found, absence of evidence would not preclude a role for a Designer.

The greater problems with intelligent design from a scientific perspective show up when we test it against the hallmarks of science. In particular, ID is clearly incompatible with the first hallmark—that science seeks explanations for observed phenomena that rely solely on natural causes. The very idea of a transcendent Designer implies something that natural processes cannot explain, no matter whether the Designer is or isn't explicitly named as God. As a result, some ID proponents have sought to redefine science to allow nonnatural explanations. The problem with such a redefinition is that it would render science impotent. As a simple analogy, consider the collapse of a bridge. You can choose to believe that the collapse was an act of God, and you might well be right—but this belief won't help you design a better bridge. We learn to build better bridges only by assuming that collapses happen through natural causes that we can understand and learn from. In precisely the same way, it is the scientific quest for a natural understanding of life that has led to the discovery of relationships among species, genetics, DNA, and much of modern agriculture and medicine. Many of the scientists who made these discoveries, including Charles Darwin himself (see the quotation at the beginning of this chapter), believed deeply that they could see God's hand in creation. But if they had let their belief stop them from seeking natural explanations, they would have discovered nothing.

Intelligent design also fails to be in accord with the second and third hallmarks of science, because it does not offer a predictive model that can be tested. The assumption of a Designer might or might not be correct, but it does not tell us how life would be different from what we'd see if there were no Designer. Moreover, as we've discussed, scientists continually modify the theory of evolution as new evidence requires. In the unlikely event that we found evidence that strongly contradicted the current theory—for example, fossil evidence proving that people and dinosaurs existed at the same time—scientists would willingly discard the theory and go back to the drawing board. In contrast, because most proponents of intelligent design are motivated by their religious faith, their belief in ID is unshakable.

The bottom line is that science and faith are different things, and the relative worth of one does not override the worth of the other. Whether you choose to believe the theory of evolution is up to you, and if you do believe it, you can choose whether to believe that it occurred through random chance or with the help of a guiding hand. But whatever your beliefs, the theory of evolution is a clear and crucial part of modern science, and it is integral to an understanding and appreciation of modern biology. And more important for the discussion in this book, the theory of evolution frames our ideas about how to search for life beyond Earth. No competing model offers any similar scientific benefits.

THE BIG PICTURE

Putting Chapter 5 in Perspective

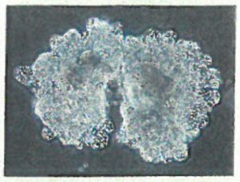
In this chapter, we have surveyed the nature of life on Earth and explored some of the implications of this survey for the search for life elsewhere. As you continue in your studies, keep in mind the following "big picture" ideas:

- If we are going to search for life, it's useful to think about just what it is we are searching for. Defining life turns out to be surprisingly difficult, but at a minimum it seems that life must be capable of reproducing and evolving. Thus, evolution plays a central role in the definition of life as well as in our understanding of life on Earth.
- Life on Earth has at least three key features that are likely to be shared by any life we find elsewhere: (1) Life has a fundamental structural unit, which we call the cell; (2) living cells undergo metabolism, by which we mean chemical reactions that keep the cells alive; and (3) living cells have a heredity molecule, which is DNA for life on Earth, that allows them to store their operating instructions and to pass these instructions to their offspring.
- Life on Earth survives under a much wider range of conditions than we would have guessed a few decades ago, suggesting that life elsewhere might similarly be found in a fairly broad range of environments. This fact greatly increases the number of worlds on which we might hope to find life.

SUMMARY OF KEY CONCEPTS

5.1 DEFINING LIFE

• What are the general properties of life on Earth?



Six key properties of life on Earth are order, reproduction, growth and development, energy utilization, response to the environment, and evolutionary adaptation.

• What is the role of evolution in defining life?

The **theory of evolution,** which holds that life changes over time through the mechanism of **natural selection,** is the unifying principle of modern biology. It holds this central role because it successfully explains all the other properties of life, the observations we make in the geological record, and the observations we make of relationships among living organisms.

• What is life?

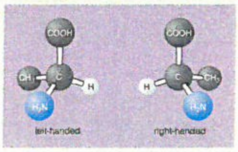
No known definition of life works in all circumstances, but for most purposes the following definition will suffice: Life is something that can reproduce and evolve through natural selection.

5.2 CELLS: THE BASIC UNITS OF LIFE

• What are living cells?

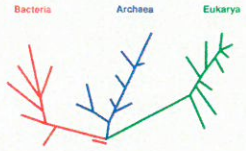
Cells are the basic units of life on Earth, as they serve to separate the living matter inside them from the outside world. The barrier that marks this separation is called the **cell membrane.**

• What are the molecular components of cells?



The major molecular components of cells fall into four main classes: **Carbohydrates** are sugars and starches that provide energy and build many cellular structures; **lipids,** which include fats, are the main ingredients of structures including cell membranes and also store cellular energy; **proteins** play a vast number of roles in cells, and the proteins known as **enzymes** act as **catalysts** to facilitate biochemical reactions; **nucleic acids,** which include **DNA** and **RNA,** are most important for the roles they play in heredity. Commonalities among the molecules used in different organisms, such as the fact that all life on Earth builds proteins from only left-handed versions of **amino acids,** provide strong evidence for the idea that all life evolved from a common ancestor.

• What are the major groupings of life on Earth?



Modern biologists classify life into three **domains: bacteria, archaea,** and **eukarya.** The **tree of life** shows relationships among species within the three domains; note that all plants and animals are just two small branches of the eukarya.

5.3 METABOLISM: THE CHEMISTRY OF LIFE

• What are the basic metabolic needs of life?

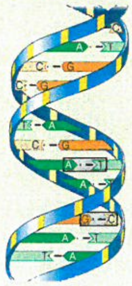
Life requires (1) a source of raw materials to build cellular structures, with carbon as the most important of these materials and (2) a source of energy to fuel metabolic processes.

• How do we classify life by its metabolic sources?

We classify life by its carbon source as either a **heterotroph,** which gets its carbon by eating, or an **autotroph,** which takes carbon directly from the environment in the form of atmospheric or dissolved carbon dioxide. We then subclassify these categories by energy source, using the prefix *photo* for life that gets energy from sunlight and the prefix *chemo* for life that gets energy either from eating or from inorganic chemical reactions.

5.4 DNA AND HEREDITY

• How does the structure of DNA allow for its replication?



The double helix of DNA consists of two strands connected by the DNA bases. The bases connect according to precise pairing rules (T attaches only to A, and C attaches only to G), so that when the strands separate, each can serve as a template for making a new DNA molecule that is identical to the original one.

• How is heredity encoded in DNA?

G		
TGT	Cysteine	T
TGC	Cysteine	C
TGA	stop	A
TGG	Tryptophan	G

The precise sequence of the bases in a DNA molecule contains the instructions for assembling proteins and other cell functions. A segment of DNA that codes for a single cell function or protein is called a **gene,** and the complete base sequence of an organism represents its **genome.** The "language" used to translate from the base sequence into proteins is called the **genetic code.**

• How does life evolve?

Life evolves because the copying of DNA is not perfect, although the error rate is quite small. The occasional, random copying errors, called **mutations,** can change the instructions in DNA. Most mutations either are lethal or have no effect at all, but a few carry benefits that can then be transmitted to offspring when the DNA replicates.

5.5 LIFE AT THE EXTREME

• What kinds of conditions can life survive?

Many living organisms can survive in a surprisingly wide range of conditions. These **extremophiles** include microbes that can survive in temperatures above the normal boiling point of water, in the dry deserts of Antarctica, deep underground in the tiny pores of rocks, and even under exposure to high levels of radiation.

• Are extremophiles really extreme?

The conditions that we consider extreme are, overall, probably more typical of the conditions found on Earth during most of its history than the conditions we enjoy on the surface today. Many other worlds may have similar conditions, suggesting that extremophiles may in fact be more common in the universe than life similar to plants and animals.

THE PROCESS OF SCIENCE IN ACTION

5.6 EVOLUTION AS SCIENCE

• Is evolution a fact or a theory?

This question offers a false choice, because fact and theory are not considered to be opposites in science. Evolution is a well-confirmed theory based on a wide variety of observational and experimental evidence.

• Are there scientific alternatives to evolution?

While there are many alternative explanations for our existence, including ideas such as creation science or intelligent design, none of these ideas qualifies as a *scientific* alternative to evolution.

EXERCISES AND PROBLEMS

REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. Briefly describe the six key properties that appear to be shared by most living organisms on Earth.
2. What is *natural selection?* Summarize the logic by which Darwin came to the "inescapable conclusion" that evolution occurs by natural selection. Describe some of the evidence that supports Darwin's *theory of evolution*.
3. Briefly describe the evidence that points to a single common ancestor for all life on Earth.
4. Why do we say that living cells are *carbon-based?* Briefly discuss whether life elsewhere could be based on something besides carbon.
5. Briefly describe each of the four main classes of cellular molecules: *carbohydrates, lipids, proteins,* and *nucleic acids.* What are *enzymes,* and where do they fit into this picture?
6. What are *amino acids?* What do we mean by their *handedness?* How do amino acids offer further evidence for a common ancestor for all life on Earth?
7. What are the three *domains* of life? Which domain do we belong to?
8. What do we mean by the *tree of life?* List three important ideas that we learn from the tree and that differ from older ideas about biology.
9. What is *metabolism,* and what are the two basic metabolic needs of any organism? Explain the four metabolic classifications listed in Table 5.1.
10. Why is water so important to life on Earth? List the three major roles that water plays in metabolism.
11. Describe the double helix structure of DNA. How does a DNA molecule replicate?
12. What is a *gene?* A *genome?* The *genetic code?*
13. What are *mutations,* and what effects can they have? Briefly explain why mutations represent the molecular mechanism of natural selection.
14. What are *extremophiles?* Give several examples of organisms that live in extreme environments. What are the implications of the existence of extremophiles for the search for extraterrestrial life?
15. Describe several ways in which the theory of evolution is analogous to the theory of gravity.
16. Explain how evolution exhibits each of the three hallmarks of science, and discuss why alternatives such as creationism and intelligent design do not show these hallmarks.

TEST YOUR UNDERSTANDING

Surprising Discoveries?

Suppose we found an organism on Earth with the characteristics described. In light of our current understanding of life on Earth, should we be surprised to find such an organism existing? Why or why not? Explain clearly; because not all of these have definitive answers, your explanation is more important than your chosen answer.

17. A single-celled organism that builds proteins using 45 different amino acids.

18. A single-celled organism that lives deep in peat bogs, where no oxygen is available.
19. A multicellular organism that reproduces without passing copies of its DNA to its offspring.
20. A single-celled organism that can survive in a dormant state even in the complete absence of any liquid water.
21. A multicellular organism that can grow and reproduce even in the absence of water.
22. A bacterium with cells that lack the molecule ATP.
23. A species of archaea that lives in the 1000°C molten rock of a volcano.
24. A species of archaea that lives in the walls of a nuclear reactor.
25. Two different animal species whose genomes are more than 99% identical.
26. A species of bacteria that has a genome 99% identical to that of humans.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Which of the following is *not* a key property of life? (a) the maintenance of order in living cells; (b) the ability to evolve over time; (c) the ability to violate the second law of thermodynamics.
28. *Natural selection* is the name given to (a) the occasional mutations that occur in DNA; (b) the mechanism by which advantageous traits are preferentially passed on from parents to offspring; (c) the idea that organisms can develop new characteristics during their lives and then pass these to their offspring.
29. Which of the following is *not* considered a key piece of evidence supporting a common ancestor for all life on Earth? (a) the fact that all life on Earth is carbon-based; (b) the fact that all life on Earth uses the molecule ATP to store and release energy; (c) the fact that all life on Earth builds proteins from the same set of left-handed amino acids.
30. An organism's heredity is encoded in (a) DNA; (b) ATP; (c) lipids.
31. An enzyme consists of a chain of (a) carbohydrates; (b) amino acids; (c) nucleic acids.
32. Which of the following is *not* a source of energy for at least some forms of life on Earth? (a) inorganic chemical reactions; (b) energy release from plutonium; (c) consumption of preexisting organic compounds.
33. People belong to domain (a) eukarya; (b) archaea; (c) bacteria.
34. Which of the following mutations would you expect to have the greatest effect on a living cell? (a) a mutation that changes a single base in a region of noncoding DNA; (b) a mutation that changes the third letter of one of the three-base "words" in a particular gene; (c) a mutation that deletes one base in the middle of a gene.
35. Generally speaking, an *extremophile* is an organism that (a) thrives in conditions that would be lethal to humans and other animals; (b) could potentially survive in space; (c) is extremely small compared to most life on Earth.
36. Based on what you have learned in this chapter, it seems reasonable to think that life could survive in each of the following habitats *except* (a) rock beneath the martian surface; (b) a liquid ocean beneath the icy crust of Jupiter's moon Europa; (c) within ice that is perpetually frozen in a crater near the Moon's south pole.

INVESTIGATE FURTHER

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

37. *Rock Life?* How do you know that a rock is not alive? In terms of the properties of life discussed in this chapter, clearly describe why a rock does not meet the criteria for being alive.
38. *The History of Evolution.* Many people assume that Charles Darwin was the first person to recognize that life evolves, but this is not true. Write a few paragraphs summarizing the history of ideas about evolution and explaining why we give Darwin credit for the theory of evolution even though he was not the first person to realize that evolution occurs.
39. *Genetic Variation.* One of the underlying facts (Fact 2 on p. 157) that explains natural selection is that individuals in a population of any species vary in many heritable traits. Based on what you have learned about the molecular basis of evolution, explain why individuals of the same species are *not* expected to be genetically identical.
40. *Artificial Selection.* Suppose you lived hundreds of years ago (before we knew about genetic engineering) and wanted to breed a herd of cows that provided more milk than cows in your current herd. How would you have gone about it? Explain, and describe how your breeding would have worked in terms of the idea of artificial selection. How does this breeding offer evidence in favor of the idea of natural selection?
41. *Ingredients of Life.* Study the ingredients of life as shown in Figure 5.5, and consider them in light of what you've learned about the overall chemical composition of the universe. Would you expect the ingredients to be rare or common on other worlds? Explain.
42. *A Separate Origin?* Suppose that we someday discover life on Mars. How might we be able to determine whether it shares a common origin with life on Earth (perhaps suggesting that life traveled on meteors between the two planets) or has a completely separate origin? Explain clearly.
43. *Dominant Life.* While most of us tend to think of ourselves as the dominant form of life on Earth, biologists generally argue that the dominant life consists of microbes of the domains archaea and bacteria. In two to three paragraphs, explain why microbes seem more dominant than us.
44. *The Human Power to Destroy.* We may have the ability to destroy ourselves today, perhaps as the result of nuclear war or perhaps through some type of environmental catastrophe. But is there anything we could do with our current abilities that would allow us to wipe out *all* life on Earth? Explain why or why not.
45. *The Search for Life.* Based on what you have learned about life on Earth, what are we searching for when we search for life elsewhere? For example, are we searching only for worlds with surface oceans and oxygen-rich atmospheres like Earth, or for something else? Write one to three paragraphs describing the types of worlds that we can consider as potential homes for life.
46. *Evolution and God.* Does the theory of evolution preclude the existence of God? Clearly explain your answer.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

47. *Atomic Numbers in Life.* A typical bacterium has a volume of about 1 cubic micrometer. A typical atom has a diameter of about 0.1 nanometer. Approximately how many atoms are in a bacterium?

48. *Oxygen Atoms in People.* Figure 5.5 shows that oxygen makes up about 65% of the mass of a human being. A single oxygen atom has a mass of 2.66×10^{-26} kg. (a) Use this fact to estimate the number of oxygen atoms in *your* body. (*Hint:* If you know your weight in pounds, you can convert to kilograms by dividing by 2.2.) (b) Compare your answer to the number of stars in the observable universe (which is roughly 10^{22}).

49. *Cellular Energy.* A typical eukaryotic cell, such as a cell in the human body, uses about 2×10^{-17} joule of energy each second. The breakdown of a single molecule of ATP (in which a phosphate separates from ATP to make ADP; see Figure 5.12) releases about 5×10^{-20} joule of energy. (a) About how many molecules of ATP must be broken down and reassembled each second to keep a eukaryotic cell alive? (b) How many times does this ATP recycling occur each *day* in a typical cell? (c) The human body has roughly 10^{14} cells. Approximately how many cycles of the ATP reaction occur each day in your body?

50. *The Genetic Code.* Suppose that, as evidence suggests, very early life on Earth used a genetic code that consisted of only two-base "words" rather than three-base "words." Could such life have made use of the same set of 20 amino acids that life uses today? Explain, using quantitative arguments.

Discussion Questions

51. *Science and Religion.* Science and religion are often claimed to be in conflict. Do you believe this conflict is real and hence irreconcilable, or is it a result of misunderstanding the differing natures of science and religion? Defend your opinion.

52. *Computer Life.* Although scientists have already developed computer programs capable of reproducing themselves and evolving, few people consider such programs to be alive. But consider future developments in computing and robotic technology. Do you think we'll ever make something based on electronics that is truly alive? Could it also be intelligent? If so, what civil rights should we give to such "artificial" intelligent life?

53. *Genetic Engineering and Future Evolution.* For billions of years, evolution has proceeded through mutations and natural selection. Today, however, we have the ability to deliberately alter DNA in what we call "genetic engineering." How do you think this ability will affect the future evolution of life? How will it affect future human evolution on Earth? Based on your answers, should we expect extraterrestrial civilizations to have naturally evolved or to be products of their own genetic engineering? Discuss and defend your opinions.

54. *Gene Transfer and GMOs.* In some cases, organisms can transfer entire genes to other organisms. This fact causes some people to worry that organisms that we have genetically engineered—commonly referred to as GMOs, for "*g*enetically *m*odified *o*rganisms"—may transfer their genes to other organisms in unexpected ways. For example, a crop engineered with a gene that gives it resistance to some pest may transfer its gene to weeds, giving them the same resistance. Discuss how GMOs might affect other organisms. Overall, what, if any, controls do you think the government should put on the use of GMOs?

Web Projects

55. *The Dover Opinion.* In December 2005, a U.S. District Court issued its opinion on a case concerning the teaching of intelligent design (ID), deciding that ID does not belong alongside evolution in science classes. The full text of the opinion, commonly called the Dover opinion, is available online. Read the opinion, and discuss its implications for the ongoing public controversy about what belongs in science classes.

56. *Darwin on Evolution.* You can find online the entire text of Charles Darwin's *The Origin of Species.* Read the final chapter, in which Darwin addresses potential criticisms of his theory. Evaluate how well he presented his case. How much stronger does the theory seem today than at the time Darwin first described it in 1859? Summarize your conclusions in a one-page essay.

57. *Extreme Life.* Look for information about a recent discovery of a previously unknown type of extremophile. Describe the organism and the environment in which it lives, and discuss any implications of the finding for the search for life beyond Earth. Summarize your findings in a one-page report.