CHAPTER 12

Prospecting for Biological Gold

Biodiversity and Classification

... is a source of this extremely valuable chemical, produced by microorganisms.

Scientists are interested in finding other useful products in Yellowstone.

Are they likely to succeed? Is there much left to discover about life?

At the end of a narrow foot trail in Yellowstone National Park lies a natural curiosity—Octopus Spring. The boiling hot water of the spring is colored an otherworldly blue. A gooey white crust encircles its main pool, and along the banks of the drainage streams radiating in all directions from it are brightly colored mats and streamers of pink, yellow, green, and orange. Although Octopus Spring is certainly not the most beautiful or dramatic feature of Yellowstone, this relatively small spring looms large in the history of biological discovery and represents a source of continued controversy.

The brilliant colors of Octopus Spring result from large numbers of microscopic organisms living in the water and on nearby surfaces. In the 1960s, Dr. Thomas Brock of the University of Wisconsin was the first to describe this biological community. One of the species he discovered, which he named *Thermus aquaticus* for its affinity for hot water, contained a protein new to science. This protein, an enzyme called *Taq* polymerase, can help produce long chains of DNA at much higher temperatures than other organisms can. *Taq* polymerase is now an integral part of the polymerase chain reaction (PCR), a high-temperature process used by many laboratories to prepare DNA samples for research or for use in the process of DNA fingerprinting. PCR has helped to revolutionize DNA research and has made many of the recent advances in genetic technology possible.

Until it was ruled invalid in 1999, the patent for *Taq* polymerase was held by the Swiss pharmaceutical firm Hoffman-LaRoche, and licensing agreements with other companies that used and produced *Taq* polymerase netted the company over $100 million every year. Of this substantial sum, Yellowstone National Park, the National Park Service, and the U.S. Treasury received... nothing in royalty payments. Even a small share of the royalties for *Taq* polymerase would have provided funds to improve and manage this heavily used national park.

The managers of Yellowstone Park do not want to miss out on the financial rewards that may come with protecting other valuable species within their borders. To capitalize on future discoveries in the park, Yellowstone entered into an agreement in 1997 with Diversa Corporation to identify and describe some of the microscopic species in the park. In return, Diversa agreed to make a one-time payment of $100,000 to Yellowstone Park and to provide several thousand dollars for research services. Diversa also agreed to share an undisclosed percentage of royalties from any profitable products that result from their research. The announcement of this deal set off a flurry of criticisms—from environmentalists who fear the disruption of biological communities in the park, to government watchdogs concerned about a few private stockholders profiting from resources taken from a park maintained for the entire public. Diversa has yet to begin exploration in Yellowstone's hot springs, pending the resolution of several legal challenges to their agreement.

Even without the legal challenges, the agreement between Yellowstone's managers and Diversa is a calculated risk by both parties. Diversa is investing nearly a million dollars in this venture, and Yellowstone faces potential damage to the wild and scenic resources that the park was designed to protect for the public good. Why are the parties to this agreement willing to take these risks? What is the likelihood of success in Diversa's search for valuable species within Yellowstone Park? Can there be many organisms that humankind has yet to discover? What do we know about the organisms we have identified? And how can we learn quickly about the traits of newly discovered species? We can answer these questions by applying evolutionary theory to investigations of the amazing variety of life on Earth.

12.1 Biological Classification

Diversa Corporation's proposed hunt for new organisms and new uses of known organisms in Yellowstone is called **bioprospecting**. Bioprospectors seek to strike biological "gold" by finding the next penicillin (originally discovered in a fungus), aspirin (produced by willow trees), or *Taq* polymerase in the living world. Yellowstone isn't the only potentially rich source of biological gold—drug companies are also investing in bioprospecting in the vast Amazonian rain forests, the strange hydrothermal vents of the ocean depths (Figure 12.1), and the bleak expanses of Antarctic ice. Other scientists are also surveying more commonly encountered organisms such as airborne molds and the bacteria that cause tooth decay. To understand the challenges associated with this survey, we must know something about the diversity of life on Earth.

How Many Species Exist?

The company name "Diversa" reflects the promise and challenge of looking for new drugs and other useful chemicals in the natural world. A characteristic of life on Earth is that it is full of variety—that is, the living world is diverse. Scientists refer to the variety within and among living species as **biodiversity**. Understanding the evolutionary origins of biodiversity and discovering the role of other species in the health of the planet is an essential aspect of biological science, but Diversa and other bioprospectors are interested in biodiversity

Figure 12.1 A source of biological riches? The organisms surrounding this deep-sea volcanic site have been known to science for less than 30 years. They represent an intriguing source of unique biological chemicals.

for a more utilitarian reason—they are banking on the variety of life to give them biochemical "solutions" to human problems.

To bioprospectors, the promise of biodiversity is its great variety, but great variety is also a source of challenge. The number of species described by science is between 1.4 and 1.8 million; even if prospectors spent only a single day screening each species for valuable products, examining them would take more than 5,000 years. The variety of different species also greatly underestimates the biodiversity within a species. Just as the species of tomato can come in many shapes, sizes, and flavors, there are species in which individuals differ greatly in the amount and potency of a particular biological molecule (Figure 12.2). Bioprospectors could miss a valuable molecule if they test only a small number of individuals from one population of a species.

Biologists disagree about the total number of species that have already been identified and described. Much of this uncertainty stems from the method of storing and cataloguing known species. When biologists identify what appears to be a new species, they collect individual specimens of the organism for storage in specialized museums. Most animal collections are found in natural history museums, while plant repositories are called herbaria (Figure 12.3); many types

Figure 12.2 Biological diversity. These varieties of the garden tomato illustrate diversity within a species.

(a) Natural history museum **(b)** Herbarium

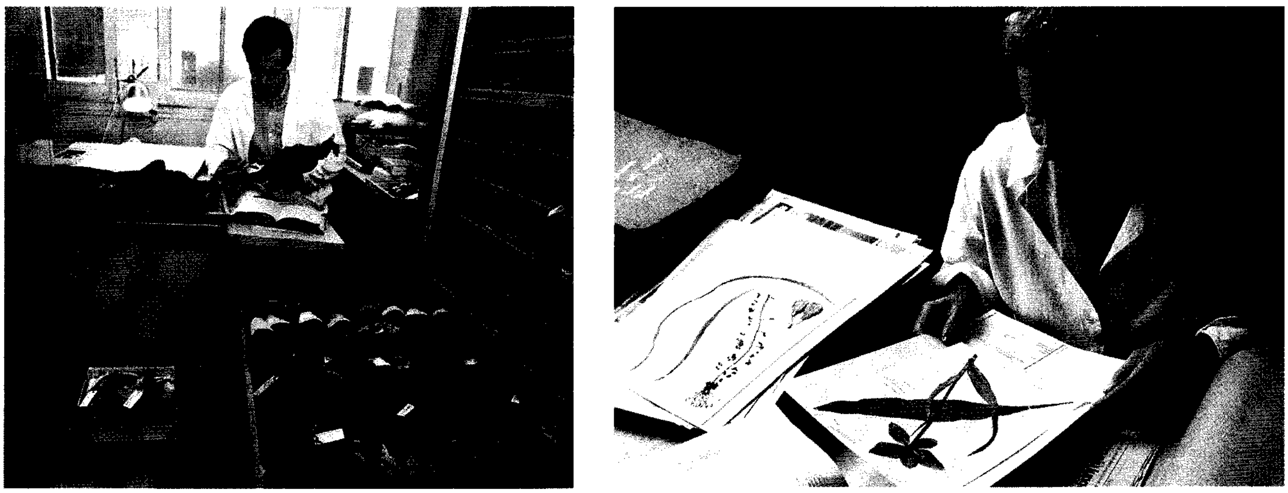


Figure 12.3 Biological collections. (a) A collection of animals in a natural history museum. Most collections contain several examples of each species to show the range of variation within the species. (b) Plant specimens are stored in herbaria.

of microbes and fungi are kept in specialized facilities called type-collection centers. **Systematists** are biologists who specialize in describing and categorizing a particular group of organisms. For an organism to be considered a new species by the scientific community, a systematist must create a description of the species that clearly distinguishes it from similar species, and she must publish this description in a professional journal. Because there are numerous large natural history museums and herbaria all over the world, along with many different journals, it is often unclear whether a species has already been described. Systematists evaluate collections to see if there is any overlap, but this process is slow and further complicated by the continual discovery and description of new species. The lack of a central resource for species collections and descriptions means that the total number of described species is only an estimate.

The number of known species represents a fraction of the total number of species on Earth. Some estimates of the actual number are as large as 100 million unique species. Most biologists agree that our planet is home to at least 10 million distinct species. Biologists are a long way from knowing all there is to know about the diversity of life. However, it is extremely rare for scientists to describe an organism that appears to have numerous features found in no other species. In fact, living species can be grouped into a few broad categories based on shared characteristics. The most general categories are kingdoms and domains.

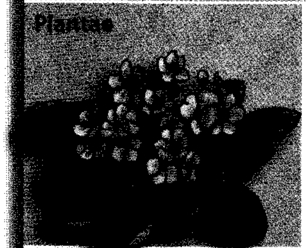
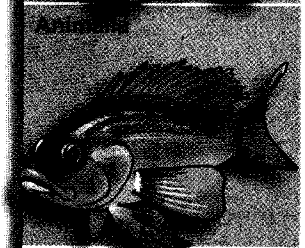
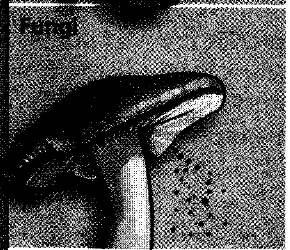
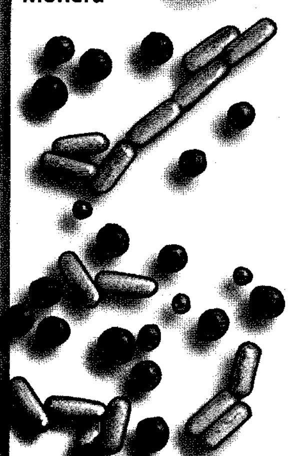
Kingdoms and Domains

Systematists work in the field of **biological classification**, in which they attempt to organize biodiversity into discrete and logical categories. The task of classifying life is much like categorizing books in a library—books can be divided into "fiction" or "nonfiction," and within each of these divisions, more precise categories can be made (for example, nonfiction can be divided into biography, history, science, etc.). The book-cataloguing system used in most public libraries, the Dewey decimal system, is only one way of shelving books. For instance, academic and research libraries use a different system, developed by the U.S. Library of Congress. Librarians use the cataloguing system that is appropriate to the collection of books owned by the library and the needs and interests of the library's users; just as there are alternative methods of organizing books, there is more than one way to organize biodiversity to meet differing needs.

Biologists have traditionally subdivided living organisms into great groups that share some basic characteristic. Fifty years ago, most biologists divided life into two categories: plants, for organisms that were immobile and apparently made their own food; and animals, for organisms that could move about and relied on other organisms for food. When it became clear that too many organisms did not fit easily into this neat division of life, some scientists began to argue for a system of five **kingdoms**, in which organisms were categorized according to the type of cell they possessed and their method of obtaining energy. Table 12.1 provides an overview of this system.

The five-kingdom system is not perfect either; for instance, the Protista kingdom contains a wide diversity of life-forms, from amoebas to seaweeds, that have only superficial similarities. More recently, many biologists have argued that the most appropriate way to classify life is according to evolutionary relationships among organisms. Recall that the theory of evolution states that all modern organisms represent the descendants of a single common ancestor that existed nearly 4 billion years ago. Evidence for this theory includes the universality of the genetic code, many cell structures, and certain biochemical pathways. Separate populations of this ancestor diverged as natural selection and genetic drift occurred in each group, resulting in evolutionary lineages as described in Chapter 11.

Table 12.1 The classification of life. Until recently, most biologists used the five-kingdom system to organize life's diversity. Now many use a six-category system, which better reflects evolutionary relationships by acknowledging the existence of three major domains as well as four of the kingdoms.

Kingdom Name	Kingdom Characteristics	Examples	Approximate Number of Known Species	Domain Name and Characteristics
Plantae 	Eukaryotic, multicellular, make own food, largely stationary	Pines, wheat, moss, ferns	300,000	**Eukarya** All organisms contain eukaryotic cells.
Animalia 	Eukaryotic, multicellular, rely on other organisms for food, mobile for at least part of life cycle	Mammals, birds, fish, insects, spiders, sponges	1,000,000	
Fungi 	Eukaryotic, multicellular, rely on other organisms for food, reproduce by spores, body made up of thin filaments called hyphae	Mildew, mushrooms, yeast, *Penicillium*, rusts	100,000	
Protista 	Eukaryotic, mostly single-celled forms, wide diversity of lifestyles, including plant-like, fungus-like, and animal-like types	Green algae, *Amoeba*, *Paramecium*, diatoms, chytrids	15,000	
Monera 	Prokaryotic, mostly single-celled forms, although some form permanent aggregates of cells	*Escherichia coli*, *Salmonella*, *Bacillus anthracis*, *Anabena*, sulfur bacteria	4,000	**Bacteria** Prokaryotes with cell wall containing peptidoglycan. Wide diversity of lifestyles, including many that can make their own food.
		Thermus aquaticus, *Halobacteria halobium*, methanogens	1,000	**Archaea** Prokaryotes without peptidoglycan and with similarities to Eukarya in genome organization and control. Many known species live in extreme environments.

The orange boxes indicate the six categories currently used to classify the diversity of life.

Five-Kingdom System

Three-Domain System

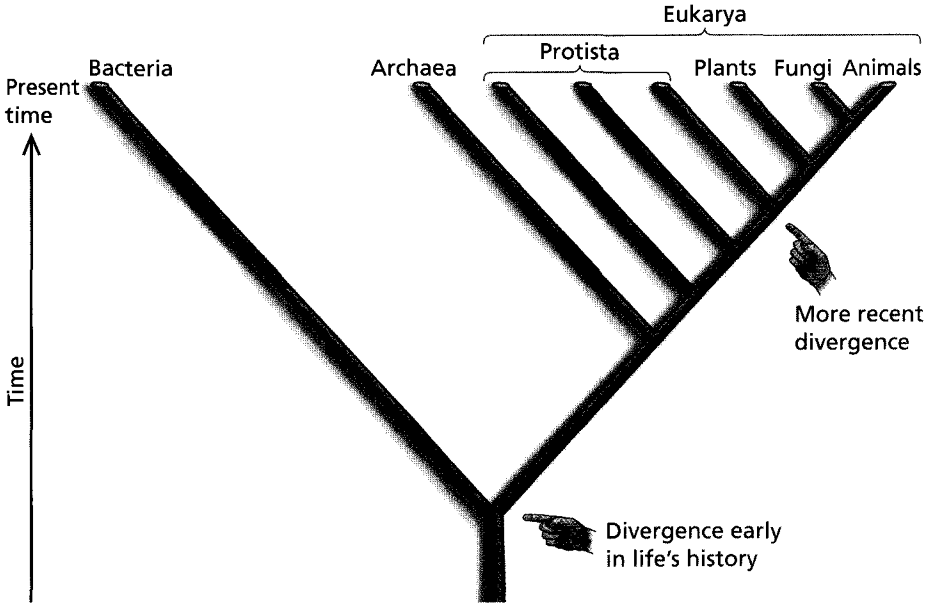


Figure 12.4 The tree of life. This tree is a simplification of the current state of knowledge regarding evolutionary relationships among living organisms. Note that the branch tips are all on the same plane, representing the present time. The tree of life has been heavily pruned through nearly 4 billion years of evolution. Living organisms represent a small remnant of all the species that have appeared over Earth's history.

The process of divergence from early ancestors into the diversity of modern species has resulted in the modern "tree of life" (Figure 12.4).

When life is classified according to the relationships among organisms, major groupings correspond to divergences that occurred very early in life's history, and minor groupings correspond to more recent divergences. Classifying life according to evolutionary relationships may be especially useful to bioprospectors if a close relationship indicates a similarity in the compounds produced by living organisms.

Determining the evolutionary relationship among *all* living organisms requires comparisons of their DNA. Since each species is unique, the DNA sequence—that is, the sequence of nucleotides within the genetic instructions—of each species is unique. However, because all species share a common ancestor, all organisms also have basic similarities in their DNA sequences. As evolutionary lineages diverged from each other, mutations in DNA sequences occurred independently in each lineage and appear now as a record of evolutionary relationship among living organisms. In other words, as described in Chapter 9, the DNA sequences of closely related organisms should be more similar than the DNA sequences of more distantly related organisms (Figure 12.5).

To determine the evolutionary relationship among all modern species, scientists must compare sequences for a gene that performs a similar function among organisms as diverse as humans, willow trees, and *Thermus aquaticus*. The DNA sequence that best fits these criteria is one containing the instructions for making ribosomal RNA (rRNA), which functions as a structural part of ribosomes. As discussed in Chapter 8, the function of ribosomes—the fundamental "factories" found in all cells—is to translate genes into proteins. Each ribosome contains several rRNA molecules. The ones primarily used by scientists who are interested in the relationships among living organisms are found in the small subunit of the ribosome. A comparison of the DNA coding for small-subunit rRNAs from myriad organisms yielded the tree diagram in Figure 12.4.

You should note from Figure 12.4 that three of the kingdoms (Fungi, Animalia, and Plantae) represent relatively recently diverged groups of organisms. What was formerly called the kingdom Monera is actually made up of two groups of organisms that are quite distinct, the Archaea and Bacteria; and the kingdom Protista is a hodgepodge of many, very different organisms. To better reflect such biological relationships, biologists categorize life into three **domains** (represented by the three main branches on the tree—Bacteria, Archaea, and Eukarya), each containing several kingdoms. These three domains represent the descendants of the most ancient divergence of living organisms.

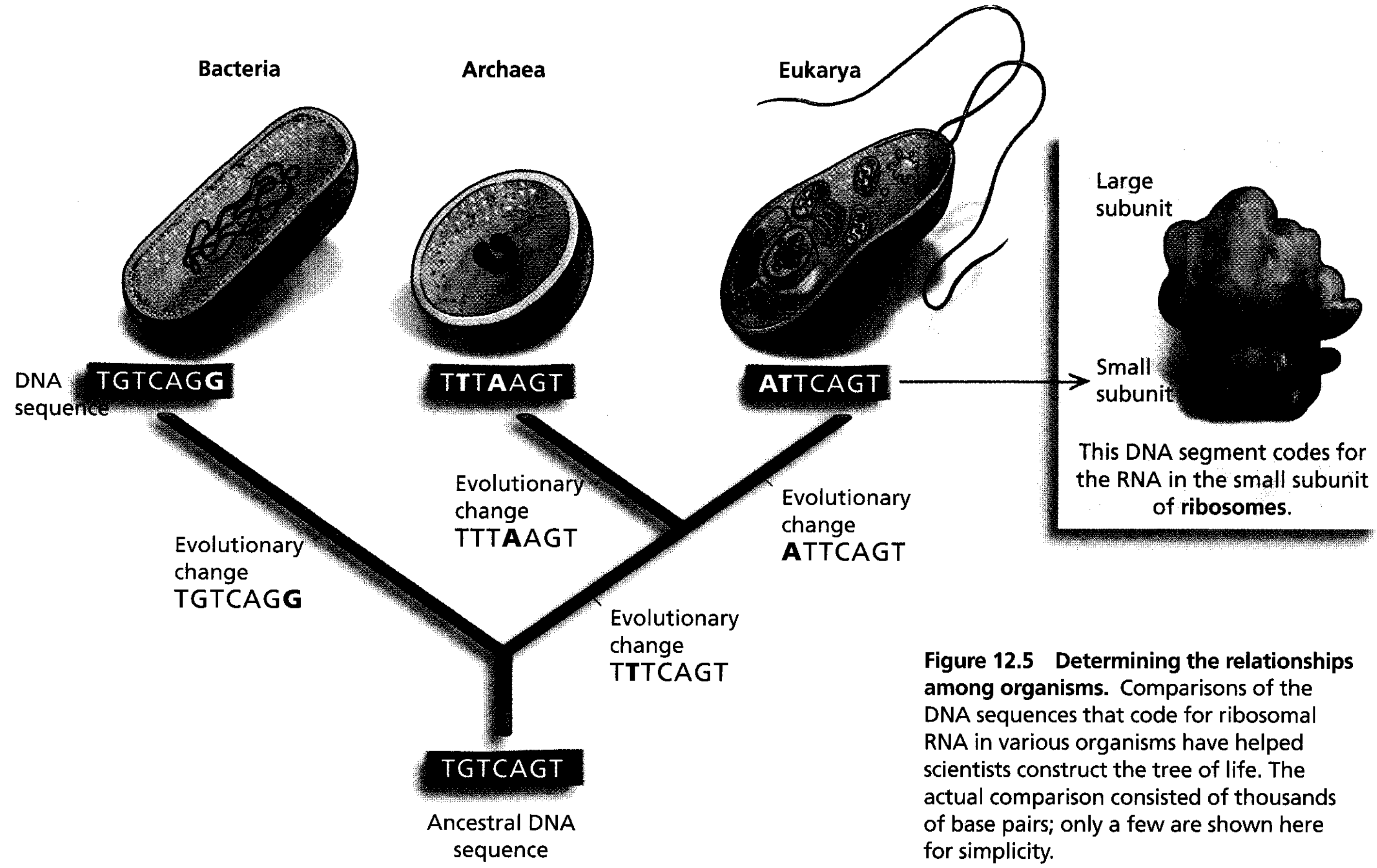


Figure 12.5 Determining the relationships among organisms. Comparisons of the DNA sequences that code for ribosomal RNA in various organisms have helped scientists construct the tree of life. The actual comparison consisted of thousands of base pairs; only a few are shown here for simplicity.

Systematists have begun delineating kingdoms in the Bacteria and Archaea domains using DNA sequence comparisons, while other biologists are revising the Eukarya kingdoms so that these categories more accurately reflect evolutionary history. However, just as the Library of Congress cataloguing system is not the most appropriate organization for a public library, an evolutionary classification is not the most effective organization for the purpose of surveying diversity. In this chapter we use a common hybrid of the five-kingdom system and three-domain system that specifies six categories: the domains Bacteria and Archaea and the four Eukarya kingdoms—Protista, Fungi, Plantae, and Animalia.

12.2 The Diversity of Life

In reality, the number of kingdoms and domains into which life is appropriately classified is of minor importance to a bioprospector, but understanding more recent evolutionary relationships may be *very* important, as we will discuss in section 12.3. However, dividing life into six categories—those described in Table 12.1—simplifies *our* discussion of biodiversity and of where bioprospectors may find valuable resources within the variety of life. In this section we describe the six categories: bacteria, archaea, protists, animals, fungi, and plants.

Bacteria and Archaea

Life on Earth arose at least 3.6 billion years ago, according to the fossil record. (The origin of this life remains an intriguing scientific mystery, described in detail in Essay 9.2.) The most ancient fossilized cells (Figure 12.6) are remarkably similar in external appearance to modern **bacteria** and **archaea**. Both bacteria and archaea are **prokaryotes**; this means they do not contain a nucleus, which provides a membrane-bound, separate compartment for the DNA in

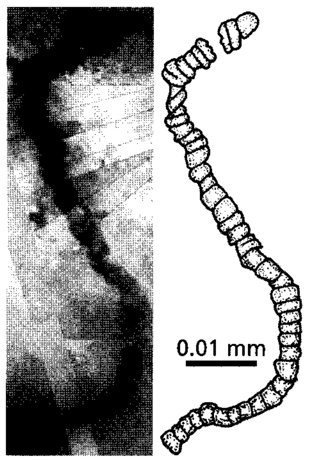
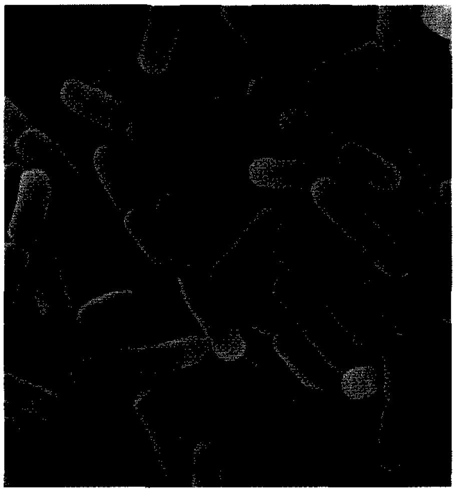
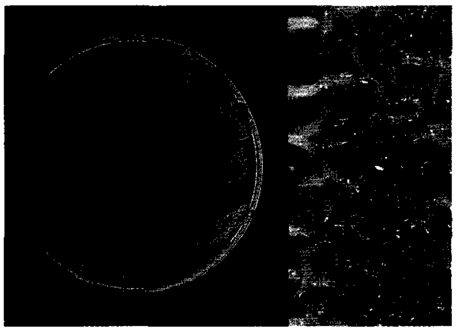


Figure 12.6 The oldest form of life. This photograph of a fossil is accompanied by an interpretive drawing showing the fossil's living form. It was found in rocks dated at 3.465 billion years old.

(a) *Escherichia coli*



(b) *Streptomyces venezuelae*



(c) *Halobacterium*

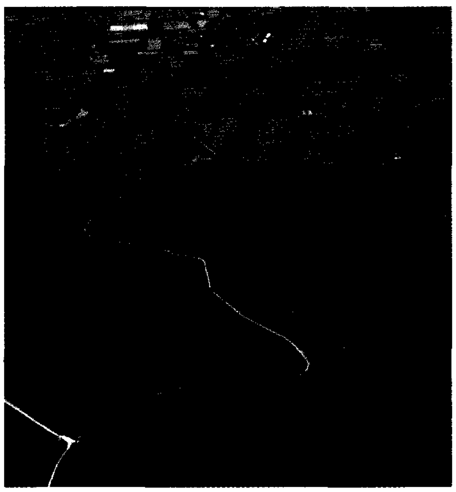


Figure 12.7 A diversity of prokaryotes. (a) *Escherichia coli*, the "lab rat" of basic genetic studies, lives on the partially digested food in our intestines. (b) A colony of billions of cells of *Streptomyces venezuelae*, source of the antibiotic chloramphenicol and a member of the group of bacteria that live in soil and decompose dead plant matter. (c) *Halobacterium*, a salt-loving archaean, is found in high populations in this salty pond. The red pigment in this bacterium's cells is very similar in structure to the light-sensing pigments in our eyes and is used to convert energy from sunlight into cellular energy.

other cells. Prokaryotes also lack other internal structures bounded by membranes, such as mitochondria and chloroplasts, which are found in more complex **eukaryotes**. Although some species may be found in chains or small colonies as in Figure 12.6, most prokaryotes are **unicellular**, meaning that each cell is an individual organism. The discarded kingdom name "Monera" (from the Greek *moneres*, meaning "single" or "alone"), which once applied to all prokaryotes, refers to this trait. Individual prokaryotic cells are hundreds of times smaller than the cells that make up our bodies; for this reason, they are often called microorganisms or **microbes**, and biologists who study these organisms (as well as single-celled eukaryotes) are known as **microbiologists**. Their small size, easily accessible DNA, and simple structure make prokaryotes very attractive to bioprospectors because the process of studying, growing, and manipulating these organisms is typically less difficult than with eukaryotes.

The relatively simple structure of prokaryotes belies their incredible chemical complexity and diversity. Some prokaryotes can live on petroleum, others on hydrogen sulfide emitted by volcanoes deep below the surface of the ocean, and some simply on water, sunlight, and air (Figure 12.7). Prokaryotes are ubiquitous—they are found in and on nearly every square centimeter of Earth's surface, including very hot and very salty places, and even thousands of feet below ground. Prokaryotes are also incredibly numerous; for instance, there are more prokaryotes living in your mouth right now than the total number of humans who have ever lived!

Domain Bacteria. Although most are harmless to humans, the majority of the well-known bacteria have been identified because they cause disease in humans or crops. While enormous efforts are expended to control these organisms, the fact that they can live in and on other living creatures is remarkable. To survive within a host organism, bacteria must escape eradication by their host's infection-fighting system. Therefore, the molecules that allow bacteria to effectively colonize in or on living humans could be useful in treating diseases of the human immune system. Disease-causing organisms thus, surprisingly, represent one source of bacterial "biological gold."

Many of the known bacteria obtain nutrients by decomposing dead organisms. Bacterial species that function as decomposers often have competitors for their food sources—other species that also consume the same food source. When many individuals compete for the same resource, natural selection will cause the evolution of traits that provide an edge over the competition. In the case of competing bacterial decomposers, this edge is often in the form of chemicals such as **antibiotics** that kill or disable other bacteria with which the decomposers may be competing. Today, more than half of commercial antibiotics are derived from bacterial prokaryotes. Another class of valuable molecules that has evolved as a result of competition among bacteria is restriction enzymes, proteins that can chop up DNA at specific sequence sites and thus interfere, or restrict, the growth of other organisms. Restriction enzymes are used in the production of DNA fingerprints and were crucial to the success of the Human Genome Project, an effort to describe the entire DNA sequence of humans. Bioprospectors are very interested in finding more of both of these extremely valuable compounds—antibiotics and restriction enzymes—within the domain Bacteria.

Domain Archaea. Although superficially similar to domain Bacteria because of its prokaryotic cells, the domain Archaea differs from Bacteria in many fundamental ways, including the structure of cells and membranes. The known Archaea encompass numerous organisms found in extreme environments, including high-salt, high-sulfur, and high-temperature habitats. *Thermus aquaticus*, the source of *Taq* polymerase and a hot-spring dweller, belongs to Archaea. *Taq* polymerase is valuable because it operates at a high temperature—making it, along with compounds from other hot-spring archaeans, potentially useful in industrial settings. Natural selection of archaea in extreme environments has likely caused the evolution of other unique and useful biological molecules that can operate at high temperatures, high pressures, or in extremely salty environments in this group of organisms.

Scientists and bioprospectors still have much to learn about bacteria and archaea, beginning with a basic understanding of exactly how diverse they are. For instance, although most archaeans are known from extreme environments, members of this domain are found everywhere they are sought. Some scientists estimate that the number of undescribed prokaryotic species could range up to 100 million. Diversa Corporation's focus on the microscopic organisms of Yellowstone Park reflects the effort that drug companies are putting into microbial bioprospecting. However, prokaryotes are not the only microscopic organisms; most species in the diverse kingdom Protista also cannot be seen with the naked eye.

Protista

The kingdom **Protista** is made up of the simplest known eukaryotes—organisms composed of cells containing a nucleus and other membrane-bound internal structures. Most protists are single-celled creatures, although several have enormous multicellular (many-celled) forms.

The most ancient fossils of eukaryotic cells are approximately 2 billion years old, nearly 1.5 billion years *younger* than the oldest prokaryotic fossils. According to the **endosymbiotic theory** for the origin of protists, eukaryotes were most likely the descendants of a "confederation" of cells. At least some eukaryotic cell structures, including mitochondria, the cell's power plants, appear to have descended from bacteria that took up residence inside (*endo-*) ancestral eukaryotic cells. When organisms live together, the relationship is known as a *symbiosis*. In this case the relationship was mutually beneficial, and over time, the cells became inextricably tied together (Figure 12.8). When biologist Lynn Margulis first popularized the endosymbiotic hypothesis in the United States in 1981, many of her colleagues were skeptical, but an examination of the membranes, reproduction, and ribosomes of mitochondria shows clear similarities to the same features in certain bacteria. Even more convincingly, the sequence of DNA found in mitochondria (mtDNA) is most similar to the DNA sequence found in a particular group of bacteria. Mutually beneficial symbioses between eukaryotic cells and photosynthetic bacteria appeared after the evolution of mitochondria. These endosymbioses led to the evolution of chloroplasts—one relationship led to green algae and land plants, while several other instances of endosymbiosis led to other modern groups, including red algae and brown algae.

Not long after the first eukaryotes appeared, a wide diversity of eukaryotic forms established themselves on Earth. The modern kingdom Protista contains organisms resembling animals, fungi, and plants. There is no agreement among scientists regarding how many **phyla**, that is, groups below the level of kingdom, are contained within Protista. Some argue as few as eight, and others

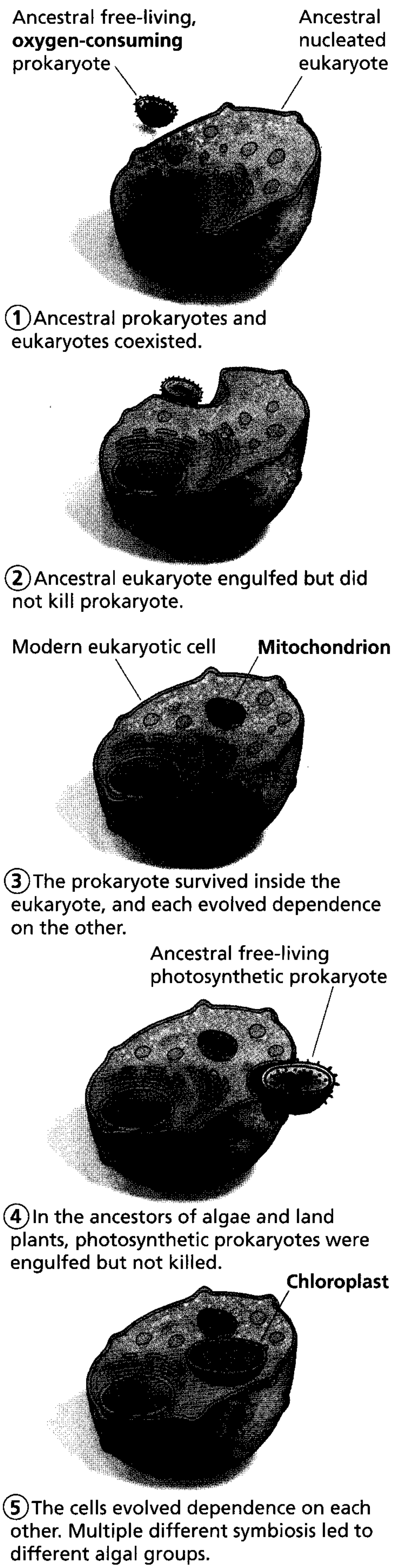
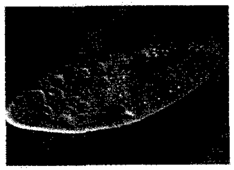
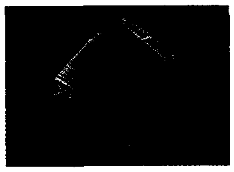


Figure 12.8 The evolution of eukaryotes. The leading hypothesis regarding the evolution of eukaryotes is endosymbiosis. Mitochondria and chloroplasts appear to be descendants of once free-living bacteria that took up residence within an ancient nucleated cell.

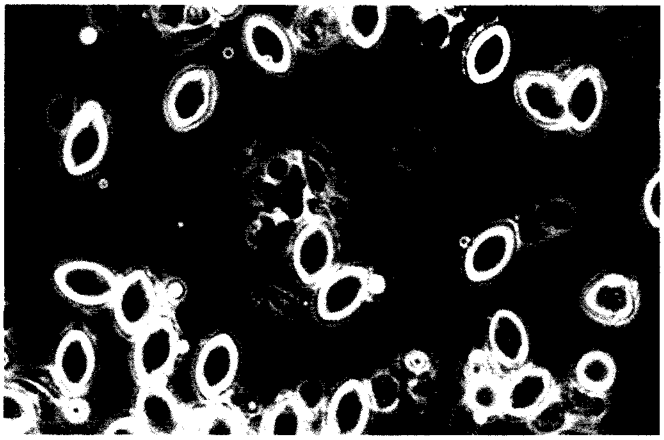
Table 12.2 The diversity of Protista. Protista contains animal-like, fungus-like, and plant-like organisms. A sampling of protistan phyla is described here.

Kingdom Protista: Common Names and Characteristics of Select Phyla		Example	
Animal-like Protists	**Ciliates** Free-living, single-celled organisms that use hair-like structures to move.	Paramecium	
	Flagellates Use one or more long whip-like tail for locomotion. Most are free-living but some cause disease by infecting human organs.	Giardia	
	Amoebas Flexible cells that can take any shape and move by extending pseudopodia ("false feet").	Amoeba	
Fungus-like Protists	**Slime molds** Feed on dead and decaying material by growing net-like bodies over a surface or by moving about as single amoeba-like cells.	Physarum	
Plant-like Protists	**Diatoms** Single cells encased in a silica (glass) shell.	Diatom	
	Brown algae Large multicellular seaweeds.	Kelp	
	Green algae Closest relatives to land plants. Single-celled to multicellular forms.	Volvox	

propose as many as 80. Table 12.2 lists a few of the more common groups of organisms within the kingdom. As a result of its diversity, kingdom Protista may contain a plethora of useful organisms and compounds (Figure 12.9). As with Bacteria and Archaea, most members of kingdom Protista remain unknown.

The group of protists that bioprospectors have investigated in the most detail are **algae**, the only members of this kingdom with the ability to manufacture food. As with plants, algae make food with the aid of sunlight via the process of photosynthesis. The photosynthetic production of carbohydrates by algae represents a rich and tempting food source to non-photosynthetic organisms that will eat, or prey on, photosynthesizers. As a result, natural selection in

(a) Animal-like protist

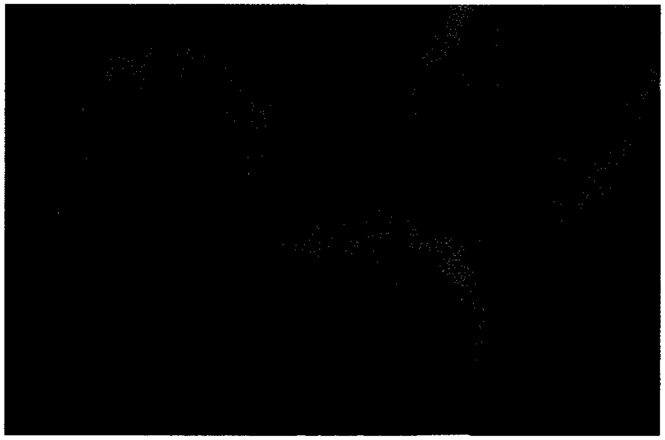


Mattesia oryzaephili, a parasite that infests and kills beetles in stored grain. *M. oryzaephili* may be useful in controlling these pests.

(b) Fungus-like protist

Lagenidium giganteum, used to control mosquito populations.

(c) Plant-like protist



Gonyaulax polyedra, a luminescent alga used to measure levels of toxic materials in ocean sediments.

(d) Plant-like protist

Chondrus crispus, a red alga that is the source of carageenan.

Figure 12.9 Protista. Protista is the most diverse of life's kingdoms. Valuable organisms and compounds have been found in many major groups, including animal-like forms (a), fungus-like forms (b), and plant-like forms (c) and (d).

most photosynthetic organisms including algae has favored the evolution of defensive chemicals. These molecules make the algae distasteful or even poisonous to a potential predator; therefore, we humans can use these chemicals to control *our* predators. For example, extracts of red algae stop the reproduction of several different viruses in human tissues grown in laboratory dishes; this effect is presumably related to the algae's defensive chemicals. As yet, no drugs derived from algae are available to consumers, although there is significant interest in developing these drugs as treatments for HIV, influenza, and severe acute respiratory syndrome (SARS), as well as other dangerous viruses.

The group of organisms commonly referred to as algae is actually made up of several distinct, quite divergent, categories of organisms. Each of these algal phyla have methods of producing and storing food that is quite different from the others, as each represents the descendants of unique endosymbiosis. Some of the unique compounds produced by different algal phyla are potentially useful to humans. For example, carageenan is a slimy carbohydrate produced by red algae (see Figure 12.9d). Red algae is commercially harvested from ocean algal beds for its carageenan, which is then used as a stabilizer and thickener in foods, medicines, and cosmetics.

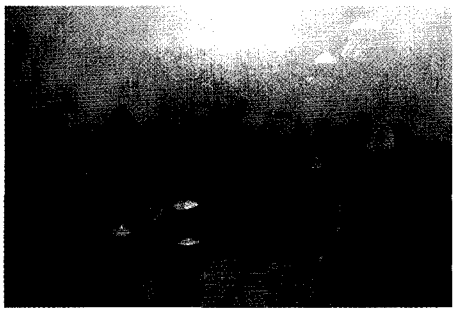


Figure 12.10 Ediacaran fauna. This reconstruction of multicellular organisms that lived before the Cambrian explosion is based on 580-million-year-old fossil remains. Note some of the bizarre forms that preceded the ancestors of modern multicellular organisms.

The animal-like and fungus-like protists are currently less interesting to most bioprospectors, presumably because animals and fungi have not been as rich a source of useful biological products as photosynthesizers have. However, as we shall see, both the kingdom Animalia and the kingdom Fungi have some intriguing characteristics and can be a source of useful biochemicals. It may be that within these categories of protists, bioprospectors also will find natural products that humans can use.

Animalia

From the origin of the first prokaryote until approximately 600 million years ago, life on Earth consisted only of single-celled creatures. Then, multicellular organisms first began to appear in the fossil record. (Note that there is some disagreement about when multicellular organisms first appeared. In 2002, Australian scientists announced that they had found evidence of multicellular life from at least 1.2 billion years ago. This date is nearly twice as old as most other estimates.) The ancient, many-celled creatures of 600 million years ago, called the Ediacaran fauna, were organisms unlike any modern species, including giant fronds and ornamented disks (Figure 12.10). Biologists are unsure which of these species is the common ancestor of modern animals—defined as multicellular organisms that make their living by ingesting other organisms and are motile (have the ability to move) during at least one stage of their life cycle. Within about 40 million years of the first appearance of the early multicellular organisms pictured in Figure 12.10, *all* modern animal groups had emerged.

The apparent relatively sudden emergence of the modern forms of animals—a period comprising little more than 1% of the history of life on Earth—is referred to as the **Cambrian explosion**, named for the geologic period during which it occurred. One of the most compelling questions in biology is the source of this explosion of biodiversity. The relatively rapid evolution of the immense diversity of life from simpler ancestors is remarkable. Some scientists hypothesize that the evolution of the animal lifestyle itself—that is, as predators of other organisms—led to the Cambrian explosion.

It can be difficult to conceive of an animal as complex as a human ever evolving from a simple eukaryotic ancestor. However, humans are actually not very different from other eukaryotic organisms. When the first cell containing a nucleus appeared, all of the complicated processes that take place in modern cells, such as cell division and cellular respiration, must have evolved. When the first multicellular animals appeared, many of the complex processes required to maintain these larger organisms, such as communication systems among cells and the formation of organs and organ systems, arose. Although a human and a starfish appear to be very different, the way they develop and the structures and functions of their cells and common organs are nearly identical. In fact, there appears to be surprisingly little genetic difference between humans and starfish; most of that difference occurs in a group of genes that control **development**, the process of transforming from a fertilized egg into an adult creature. Additionally, the amount of time since the divergence of the major evolutionary lineages of animals is still quite long—so long that it can be difficult to grasp.

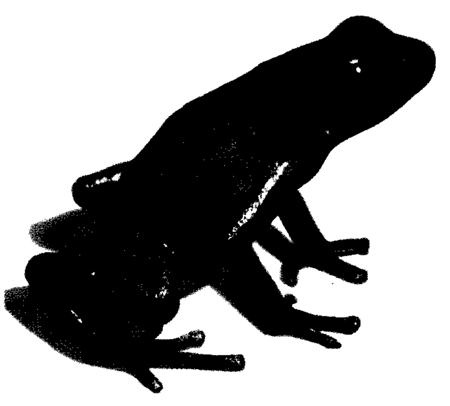
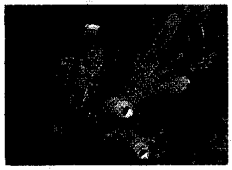
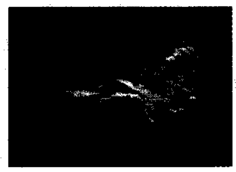
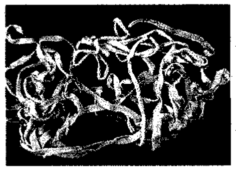
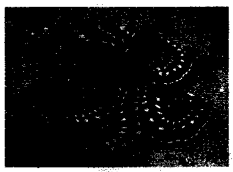
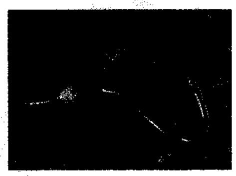
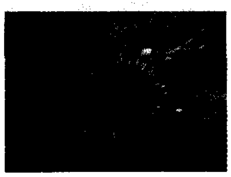
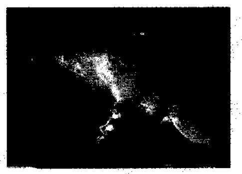


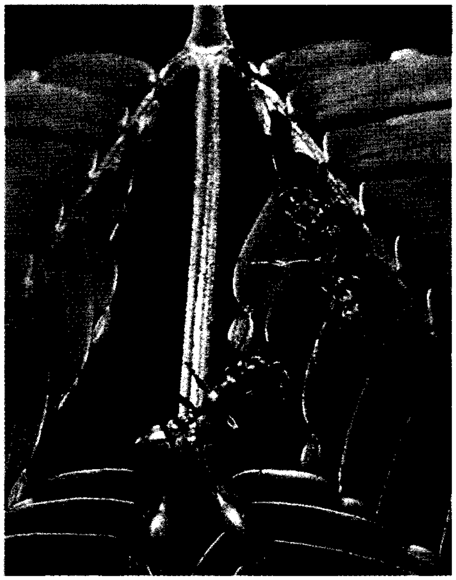
Figure 12.11 Poison dart frog. This brightly colored frog contains glands in its skin that release poison when the frog is handled. The frog's bright colors warn potential predators of its toxicity.

While members of the kingdom **Animalia** (Latin *anima*, meaning "breath," or "soul") share basic characteristics such as multicellularity and motility, there is still significant diversity within the kingdom as described by **zoologists**, the biologists who study these organisms (Table 12.3). Most people typically picture mammals, birds, and reptiles when they think of animals, but species with backbones (including mammals, birds, reptiles, fish, and amphibians) represent only 4% of the total species in the kingdom. A small number of these **vertebrates** have traits interesting to a bioprospector. For instance, poison dart frogs (Figure 12.11) secrete high levels of toxins onto their skin.

Table 12.3 Phyla in the kingdom Animalia. A sampling of the diversity of animals. The rows are arranged generally in order of appearance in evolutionary time—from the more ancient sponges to the more recent chordates.

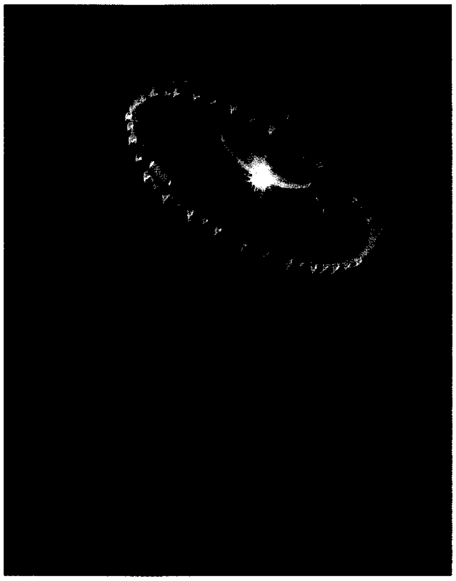
Kingdom Animalia: Major Phyla	Description	Example
Porifera	The most ancient animal group. Fixed to underwater surface and filter bacteria from water that is drawn into their loosely organized body cavity.	Sponge 
Cnidaria	Radially symmetric (like a wheel) with tentacles. Some are fixed to a surface as adults (e.g. corals), while others are free floating in marine environments.	Jellyfish 
Platyhelminthes	Flatworms with a ribbon-like from. Live in a variety of environments on land and sea, or as parasites of other animals.	Tapeworm 
Nematoda	Roundworms with a cylindrical body shape. Very diverse and widespread in many environments. Earliest animal to evolve a complete digestive tract including a mouth and anus.	Roundworm 
Mollusca	Soft-bodied animals often protected by a hard shell. Body plan consists of a single muscular foot and body cavity enclosed in a fleshy mantle. Phylum includes snails, clams, and squid.	Octopus 
Annelids	Segmented worms. Body divided into a set of repeated segments.	Earthworm 
Arthropods	Segmented animals where the segments have become specialized into different roles (such as legs, mouthparts, and antennae). Body completely enclosed in an external skeleton that molts as the animal grows. Phylum includes insects and spiders as well as crabs and lobsters.	Shrimp 
Echinoderms	Slow moving or immobile animals without segmentation and with radial symmetry. Internal skeleton with projections gives the animal a spiny or armored surface.	Sea urchin 
Chordates	Animals with a spinal cord (or spinal cord-like structure). Includes all large land animals, as well as fish, whales, and salamanders.	Duck-billed platypus 

(a) Ant (*Pseudomyrmex triplarinus*)



Source of arthritis treatment.

(b) Jellyfish (*Aequorea victoria*)



Source of fluorescent protein, a useful labeling tool in microbiology.

(c) Horseshoe crab (*Limulus polyphemus*)

Source of blood proteins used to test for pathogens in humans.

Figure 12.12 Examples of invertebrates. Most animals are invertebrates, including insects, jellyfish, and horseshoe crabs.

These toxins are nerve poisons that cause convulsions, paralysis, and even death to their potential predators. In fact, the name of these frogs derives from their traditional use by humans as a source of toxins to coat the tips of hunting darts. The nerve toxins produced by these frogs are potentially valuable to bioprospectors as sources of potent, nonaddictive painkillers—in low doses, of course.

Most of the bioprospecting work in kingdom Animalia focuses on the remaining 96% of known organisms—the **invertebrates** (animals without backbones, as shown in Figure 12.12). The vast majority of multicellular organisms on Earth are invertebrate animals, and most of these animals are insects. Many invertebrates contain chemical compounds not found elsewhere in nature. Many species of beetles, ants, bees, wasps, and spiders produce venom to repel predators and competitors; these venoms are sources of potential drugs. For example, the tropical ant *Pseudomyrmex triplarinus* produces venom that appears to be useful for treating the joint swelling and pain associated with arthritis. Ants, bees, wasps, and termites that manage to flourish in crowded colonies have evolved protective molecules that reduce the spread of disease in these environments. These organisms may prove to be a source of compounds for reducing the spread of disease in human populations as well.

The animals that inhabit the oceans' incredibly diverse coral reefs are especially interesting to bioprospectors (Figure 12.13). These biological communities are very crowded with life, and the individuals within them continually interact with predators and competitors. As a result of this challenge, many successful coral-reef organisms contain defensive chemicals that might be useful as drugs. One mantra of reef bioprospectors is, "If it is bright red, slow-moving, and alive, we want it," reflecting the assumption that in order for a marine animal to survive despite being so conspicuous and easy to catch, it must have evolved powerful deterrents to predators. The number of unknown invertebrate species, especially in the oceans, is estimated to be anywhere from 6 to 30 million.

Figure 12.13 A coral reef. This extremely diverse biological community is a rich source of interesting biological chemicals.

While our ignorance about the diversity of animals is great, another kingdom of multicellular eukaryotes is even less well known, although no less important to the functioning of ecosystems and as a source of molecules useful to humans—the fungi.

Fungi

Early classifications that separated the biological world into two kingdoms, plants and animals, placed **fungi** in the plant kingdom. Like plants, fungi are immobile, and many produce organs that function like fruit by dispersing **spores**, cells that are analogous to plant seeds in that they can germinate into new individuals. However, the mushroom you think of when you imagine fungi is a misleading image of the kingdom. Most of the functional part of fungi is made up of very thin, stringy material called **hyphae**, which grows over and within a food source (Figure 12.14).

Fungi feed by secreting chemicals that break down the food into small molecules, which they then absorb into the cells of the hyphae. The string-like form of fungal hyphae maximizes the surface over which feeding takes place, so the vast majority of the "body" of most fungi is microscopic and diffuse. Fungal food sources typically include dead organisms, and the actions of fungi are key to recycling nutrients from these organisms. Fungi are more like animals than plants in that they rely on other organisms for food. In fact, DNA sequence analysis by **mycologists**, biologists who study fungi, indicates that Fungi and Animalia are more closely related to each other than either kingdom is to the plants.

The phyla of fungi are distinguished by their method of spore formation (Table 12.4). However, convergent evolution has led to the evolution of similar body shapes and lifestyles—which we call "fungal forms" among these different phyla. One of the most commerically important fungal forms is **yeast**, a single-celled type of fungi, found in at least two different fungal phyla, that inhabits liquids such as plant sap, soaked grains, or fruit juices. The activity of yeasts in oxygen-poor but sugar-rich environments results in

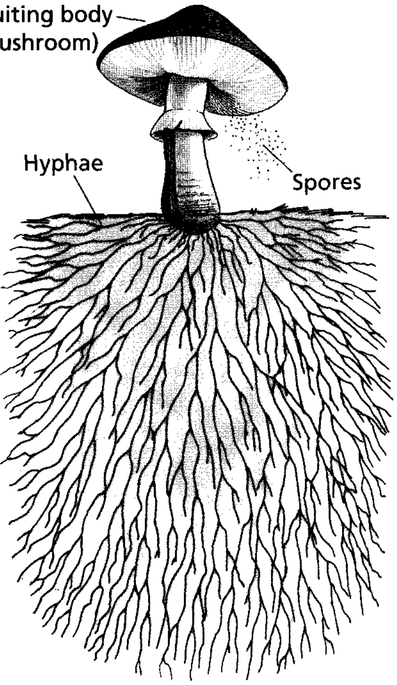
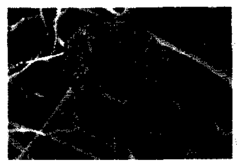


Figure 12.14 Fungi. Hyphae can extend over a large area. The familiar mushroom, as well as the fruiting structures of less-familiar fungi, primarily function only as methods of dispersing spores.

Table 12.4 Fungal diversity. Fungi are classified into phyla based on their mode of spore production. The most common phyla are listed here.

Kingdom Fungi: Major Phyla	Description	Example	
Zygomycota	Sexual reproduction occurs in a small resistant structure called a zygospore. Most reproduction is asexual— directly via mitosis.	*Rhizopus stolonifera*—bread mold	
Ascomycota	Spores are produced in sacs on the tips of hyphae in fruiting structures.	Morel	
Basidiomycota	Spores are produced in specialized club-shaped appendages on the tips of hyphae in fruiting structures.	*Amanita muscaria*—the poisonous Fly Agaric	

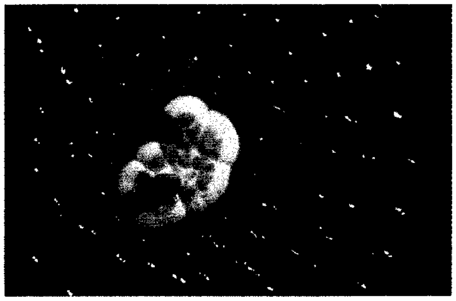


Figure 12.15 Antibiotics from fungi. The pink-and-gray mold in the center of this petri dish is a colony of *Penicillium*. The red dots on the edges of the dish are colonies of bacteria. The pink dots surrounding the *Penicillium* colony are bacterial colonies that are dying from contact with antibiotic secretions from the fungi.

the formation of alcohol, which explains the important role of these fungi in beer brewing, wine making, and the production of other forms of alcoholic beverages. The metabolism of yeasts within flour batter leads to the production of carbon dioxide bubbles, which are constrained by wheat protein fibers and thus allow the dough to "rise" during bread making. The fungal form known as **mold** is found in all phyla (another example of convergent evolution, described in Chapter 11) and is also commercially important, both because this quickly reproducing, fast-growing organism can spoil fruits and other foods and because it provides the essential activity for converting milk into certain types of cheese, including blue and Camembert.

About one-third of the bacteria-killing antibiotics in widespread use today are derived from fungi. Fungi produce antibiotics because natural selection favored the development of these chemicals as a tool to reduce populations of their main competitors for food—bacteria. Penicillin, the first commercial antibiotic, is produced by a fungus (Figure 12.15). Its discovery is one of the great examples of good fortune in science.

Before he went on vacation during the summer of 1928, British bacteriologist Alexander Fleming left a dish containing the bacteria *Staphylococcus aureus* on his lab bench. While he was away, this culture was contaminated by a spore from a *Penicillium* fungus that may have come from a different laboratory in the same building. When Fleming returned to his laboratory, he noticed that the growth of *S. aureus* had been inhibited on the fungus-contaminated culture dish. Fleming had been searching for a method to control bacterial growth, and this chance discovery provided a clue. He inferred that some chemical substance had diffused from the fungus, and he named this antibiotic penicillin, after the fungus itself. The first batches of this bacteria-slaying drug became available during World War II. Many historians believe that penicillin helped the Allies win the war by greatly reducing the number of deaths from infection in wounded soldiers. Since the discovery of penicillin, hundreds of other antibiotics have been isolated from different fungus species.

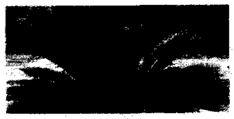
Some fungi infect living animals and thus also have potential as sources of drugs. Cyclosporin is a molecule produced by a number of different fungi as an adaptation that allows these species to infect live hosts. Cyclosporin has the effect of suppressing a host's immune response, and humans have used this effect to prevent the immune systems of organ-transplant recipients from attacking lifesaving, but foreign, transplanted organs. Fungi are also the source of a powerful class of anticholesterol drugs, called statins, that help treat and prevent heart disease. The fungus *Claviceps purpurea*, also known as ergot, has long been known to have powerful effects on the human body. Midwives throughout the nineteenth century used this pest of rye and wheat to stimulate uterine contractions and speed labor, and farmers throughout Europe knew that consuming grain infected with ergot could lead to neurological effects, including burning pain in the limbs ("St. Anthony's Fire"), hallucinations, and convulsions. Biologist Linda Caporael has suggested that the symptoms of "demonic possession" that led to the Salem Witch Trials in 1691–92 were caused by widespread consumption of ergot in contaminated grain. More recently, the illegal drug LSD has been derived from this fungus in order to produce the same hallucinogenic effects in recreational users.

While fungi have been the third most important source of molecules useful to humans—right after bacteria in terms of numbers and impacts of derived compounds—the source of most naturally derived drugs has been the plant kingdom.

Plantae

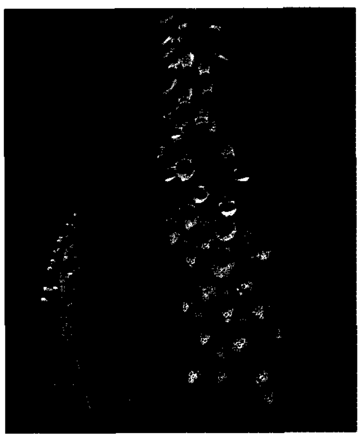
The kingdom **Plantae** consists of multicellular eukaryotic organisms that make their own food via photosynthesis. Plants have been present on land for over 400 million years, and their evolution is marked by increasingly effective

Table 12.5 Plant diversity. The four major phyla of plants are listed here in order of their appearance in evolutionary history.

Kingdom Plantae: Major Phyla	Description	Example	
Bryophyta	Mosses. Lacking vascular tissue, these plants are very short and typically confined to moist areas. Reproduce via spores.	Moss	
Pteridophyta	Ferns and similar plants. Contain vascular tissue and can reach tree size. Reproduce via spores.	Staghorn fern	
Coniferophyta	Cone-bearing plants resembling the first seed-producers.	Cycad	
Anthophyta	Flowering plants. Seeds produced within fruits, which develop from flowers. Advances in vascular tissues and chemical defenses contribute to their current dominance on Earth.	Orchid	

adaptations to the terrestrial environment (Table 12.5). The first plants to colonize land were necessarily small and close to the ground, for they had no way to transport water from where it is available in the soil to where it is needed, in the leaves. The evolution of **vascular tissue**, made up of specialized cells that can transport water and other substances, allowed plants to reach tree-sized proportions and to colonize much drier areas. The evolution of **seeds**, structures that protect and provide a food source for young plants, represented another adaptation to dry conditions on land. However, most modern plants belong to a group that appeared only about 140 million years ago, the **flowering plants**. Like their ancestors, flowering plants possess vascular tissue and produce seeds, but in addition, these plants evolved a specialized reproductive organ, the flower. Over 90% of the known plant species are flowering plants (Figure 12.16).

(a) Foxglove (*Digitalis purpurea*)

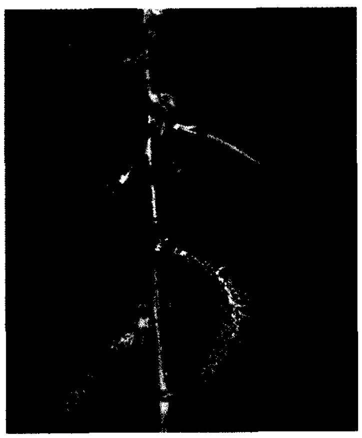


Source of heart drug digitalis.

(b) Aloe (*Aloe barbadensis*)

Source of aloe vera, used to treat burns and dry skin.

(c) Willow (*Salix alba*)



Source of aspirin.

Figure 12.16 Diversity of flowering plants. A few of the enormous variety of plants that provide important medicines.

From about 100 million to 80 million years ago, the number of distinct groups, or families, of flowering plants increased from around 20 to over 150. During this time, flowering plants became the most abundant plant type in nearly every habitat. The rapid expansion of flowering plants is called **adaptive radiation**—the diversification of one or a few species into a large and varied group of descendant species. Adaptive radiation typically occurs either after the appearance of an evolutionary breakthrough in a group of organisms or after the extinction of a competing group. For example, the radiation of animals during the Cambrian explosion is hypothesized by some scientists to be a result of the evolution of the predatory lifestyle, and the radiation of mammals beginning about 65 million years ago occurred after the extinction of the dinosaurs. Essay 12.1 describes the chronicle of life as a history of successive adaptive radiations of organisms. The radiation of flowering plants must be due to an evolutionary breakthrough—some advantage they had over other plants allowed them to assume roles that were already occupied by other species.

Plant biologists, or **botanists**, are still debating which traits of flowering plants give them an advantage over nonflowering types. Some botanists believe that the unique reproductive characteristics of flowering plants led to their radiation. These unique characteristics include preventing the allocation of nutrients to a developing embryo until successful fertilization of the egg (a process called "double fertilization"), as well the assistance of animals in transferring male gametes to the female reproductive structure

Essay 12.1 Diversity's Rocky Road

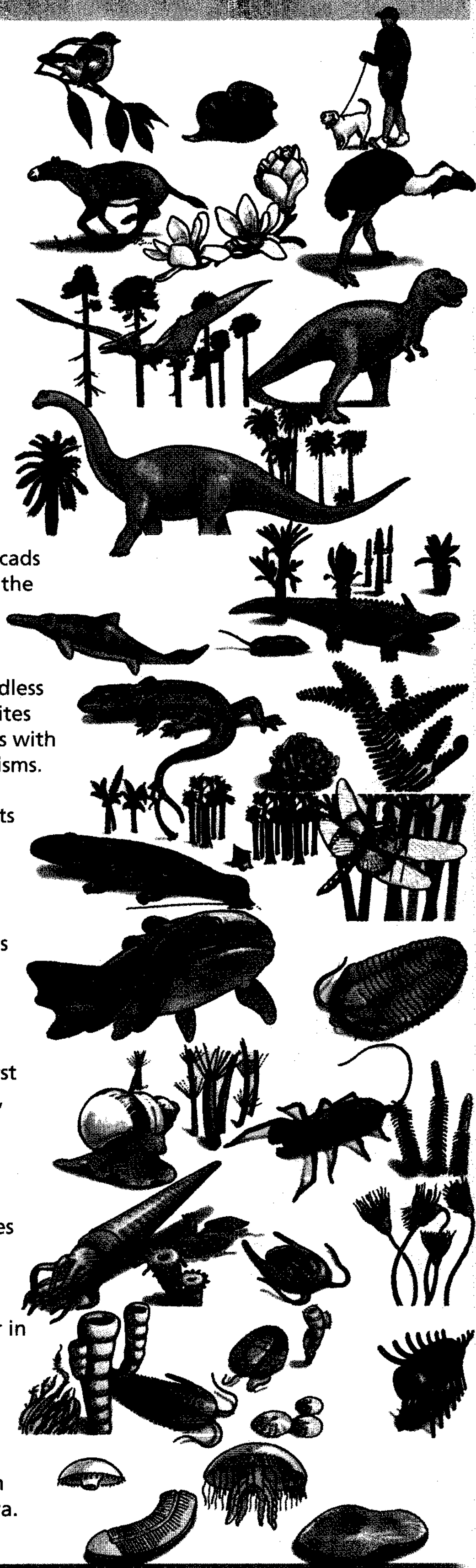
Paleontologists study fossils and other evidence of early life, and they have been able to piece together the history of life on Earth from these data. Early in this reconstruction, they recognized distinct "dynasties" of groups of organisms that appeared during different periods. The rise and fall of these dynasties allowed scientists to subdivide life's history into geologic periods. Each period is defined by a particular set of fossils. Table E12.1 gives the names of major geologic periods, their age and length, and major biological events that occurred during each period.

The dominance of a biological dynasty often ends due to mass extinctions—species losses that are rapid, global in scale, and affect a wide variety of organisms. For instance, the mass extinction of the dinosaurs (and of 60% to 80% of *all* organisms) distinguishes the division between the Cretaceous and Tertiary periods. Mass extinctions are most probably the result of a global catastrophe. Paleontologists believe that the mass extinction of the dinosaurs was most likely due to an enormous asteroid strike that occurred off the coast of what is now the Yucatán Peninsula in Mexico. This strike appears to have caused not only the incineration of large areas of forest in both North and South America but a massive, global tidal wave. It also probably threw up an enormous cloud of debris that blocked the sun's light for up to 3 months and led to a decade of severe acid rain. Organisms that were fortunate enough to survive this cataclysm, including our mammal ancestors, formed the basis of modern species. The adaptive radiation of these survivors has led to the current dynasty—the Age of Mammals.

Currently, Earth appears to be experiencing another mass extinction, this one caused by human activity. The current mass extinction is the topic of Chapter 14. The state of biological diversity—and the fate of humans—after this modern mass extinction is in doubt. But if the history of life is any indication, the next great era will be as different as the ones preceding it.

Table E12.1 Geological periods. The history of life is divided into four major eras, with all but the first era divided into several periods. Periods are marked by major changes in the dominant organisms present on Earth.

Era	Period	Millions of Years Ago	Features of Life on Earth
Cenozoic	Quaternary	0	Most modern organisms present.
		1.8	
	Tertiary		After the extinction of the dinosaurs. Mammals, birds, and flowering plants diversify.
		65	
Mesozoic	Cretaceous		Massive carnivorous and flying dinosaurs are abundant. Large cone-bearing plants dominate forests. Flowering plants appear.
		144	
	Jurassic		Huge plant-eating dinosaurs evolve. Forests are dominated by cycads and tree ferns.
		206	
	Triassic		Early dinosaurs, mammals, and cycads appear on land. Life "restarts" in the oceans.
		251	
Paleozoic	Permian		Early reptiles appear on land. Seedless plants abundant. Coral and trilobites abundant in oceans. Permian ends with extinction of 95% of living organisms.
		290	
	Carboniferous		Land is dominated by dense forests of seedless plants. Insects become abundant. Large amphibians appear.
		354	
	Devonian		Known as the age of fishes. Sharks and bony fish appear. Large trilobites are abundant in the oceans.
		408	
	Silurian		Life begins to invade land. The first colonists are small seedless plants, primitive insects, and soft-bodied animals.
		439	
	Ordovician		Life is diverse in the oceans. Cephalopods appear, and trilobites are common.
		495	
	Cambrian		All modern animal groups appear in the oceans. Algae are abundant.
		543	
Pre-Cambrian			Life is dominated by single-celled organisms in the ocean. Ediacaran fauna appear at the end of the era.
		4500	



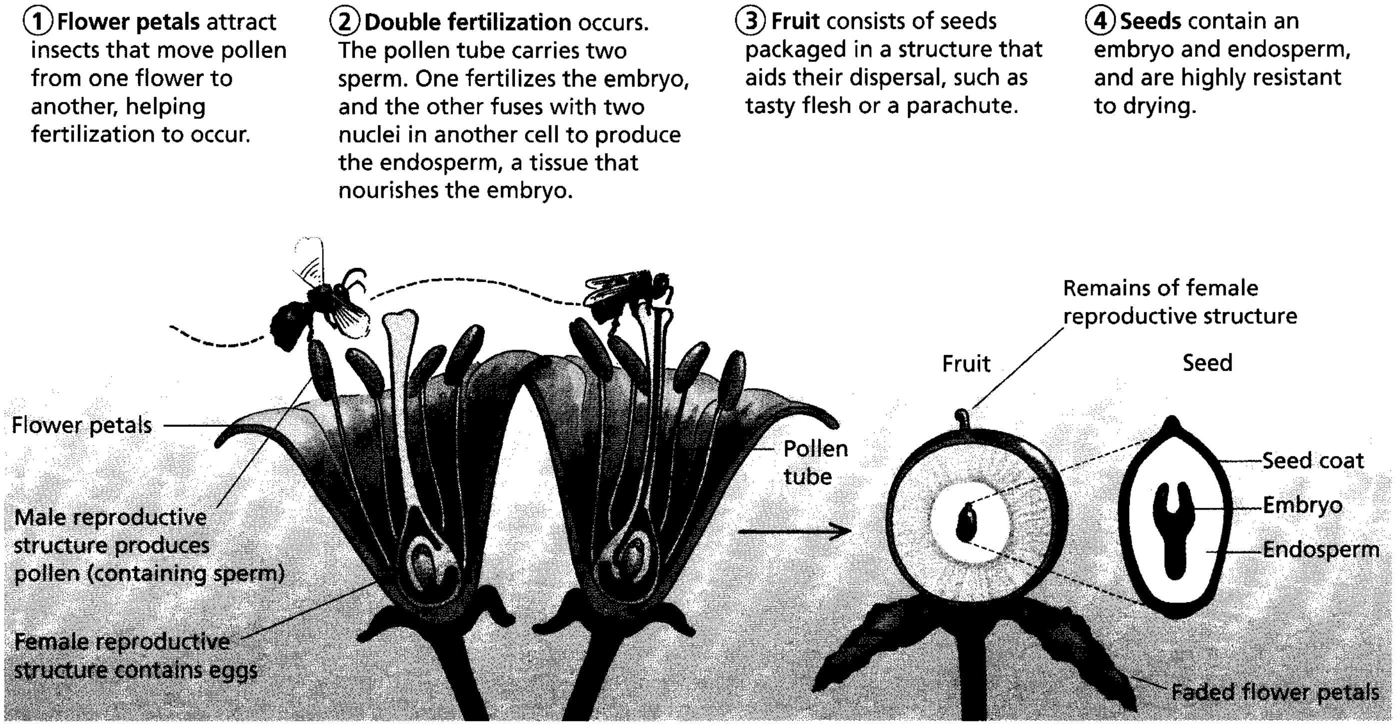


Figure 12.17 Sexual reproduction in flowering plants. Flowering plants reproduce quite differently from nonflowering plants. These differences, including the production of fruit for dispersal, may have provided their advantage over other plant types and possibly led to their adaptive radiation.

(Figure 12.17). Other botanists think that chemical defenses in these plants reduced their susceptibility to predators and provided their edge over other plant groups.

The diversity of chemical defenses in flowering plants makes them particularly interesting to bioprospectors. Because plants cannot physically escape from their predators, natural selection has favored those plants that produce predator-deterring toxins via side reactions to primary biochemical pathways. For instance, curare vines produce toxins that block the ability of nerves to control muscle tissue. Organisms that get this toxin, called curarine, in their bloodstreams become paralyzed and can do little damage to the vine. Curarine is produced via a secondary pathway of the process of amino acid synthesis; in this case, natural selection must have favored ancestors to the curare vine that had genetic variations leading to production of not only normal amino acids, but this toxic by-product as well. Today, doctors use curarine as a muscle relaxant during surgery.

The kingdom Plantae is the source of many other well-known, naturally derived drugs. Aspirin from willow, the heart drug digitalis from foxglove, the anticancer chemical vincristine from the rosy periwinkle, morphine from opium poppies, caffeine from coffee, and dozens of other pharmaceutical products are derived directly from plants. Hundreds of other drugs based on plant chemicals are now reproduced via manufacturing processes. Many botanists believe that the number of unknown plant species is relatively small—probably a few thousand—but the potential of even the known species as sources of drugs is still mostly unknown.

12.3 Learning About Species

The living world is amazingly diverse, and our knowledge of it is only fragmentary. Many biologists are attracted to the study of biological diversity for just this reason—because the variety of life is remarkable, fascinating, and largely an unexplored frontier in human knowledge. As we observed in the previous section, however, nonhuman species can also represent an enormous resource for humans. Our survey of life's diversity illustrates the essential problem for a bioprospector seeking to tap this diverse resource—there are many more potentially valuable species than there are resources to find and evaluate them. This challenge has led many drug companies to abandon most of their bioprospecting programs in favor of a strategy called "rational drug design," which allows their scientists to use an understanding of the causes of illness to create synthetic drugs used to treat a particular disease. However, many scientists have noted that some of the most effective plant-based drugs are so strange in structure that they would never have been designed through this process. Companies like Diversa are banking on finding some of these strange compounds in nature. What tools can biologists offer to bioprospectors who seek to mine biological gold?

Fishing for Useful Products

The National Cancer Institute (NCI) has taken a brute-force approach to screening species for evidence of cancer-suppressing chemicals. NCI scientists receive frozen samples of organisms from around the world, chop them up, mix them with various chemical solvents, and separate them into a number of extracts, each probably containing hundreds of components. These extracts are tested against up to 60 different types of cancer cells to evaluate their efficacy in stopping or slowing growth of the cancer. Promising extracts are then further analyzed to determine their chemical nature, and chemicals in the extract are tested singly to find the effective compound. This approach is often referred to as the "grind 'em and find 'em" strategy.

To date, this strategy has been effective in identifying one major anticancer chemical—paclitaxel, also known by the trade name Taxol, from the Pacific yew. Paclitaxel continues to be produced via extraction from the needles of other species of yew trees and is effective against ovarian cancer, advanced breast cancers, malignant skin cancer, and some lung cancers. Dozens of other less well-known anticancer drugs have been identified by this route as well.

Understanding Ecology

The grind 'em and find 'em approach works best when researchers are seeking treatments for a specific disease or set of diseases, such as cancer. But most bioprospectors are much more speculative—they are interested in determining whether an organism contains a chemical that is useful against *any* disease. Doing this effectively requires a more thoughtful approach, taking into account the biology of the species.

One aspect of an organism's biology that can be illuminating to the bioprospector is its **ecology**—that is, its relationship to the environment and other living organisms. Our survey of diversity illustrated some ecological characteristics that increase the likelihood of a species containing valuable chemicals. Some of these characteristics include high levels of competition with bacteria and fungi, susceptibility to predation, ability to live in and on other living organisms, and high population density. In each of these cases, natural selection of species in a particular ecological situation can lead to the evolution of antibacterial, antifungal, or antiviral compounds; molecules that suppress or modify the effects of the immune system; and chemical defenses that may have physiological effects. An understanding of ecology is useful even within a species. For instance, populations of plants experiencing high levels of insect attacks may produce more defensive compounds than do populations of the same species that are not under attack. Screening organisms whose ecology indicates the probability of defensive or antibiotic compounds is one method bioprospectors use to increase their success.

Reconstructing Evolutionary History

One clue to an organism's chemical traits can come from understanding its relationship to other species and knowing the traits found in its closest relatives. This is one reason some scientists argue that a classification system reflecting evolutionary relationships is more useful than one based on more superficial similarities. The classification of certain birds helps illustrate this point. Vultures (Figures 12.18a and 12.18b) are birds that specialize in feeding on dead animals. These birds spend a large amount of time soaring on broad, flat wings, have sharp beaks for tearing meat, and regurgitate food to feed their offspring. A nonevolutionary classification places all vultures together. However, research published in the 1970s demonstrates that New World vultures in the Western Hemisphere (Figure 12.18b) appear to be more closely related to storks (Figure 12.18c)—long-legged birds with long beaks that specialize in catching fish in shallow waters—than they are to Old World vultures from the Eastern Hemisphere (Figure 12.18a). Even though species of New World vulture *look* like Old World vultures, they share a more recent common ancestor with storks and are thus much more similar to storks anatomically, physiologically, and genetically.

An **evolutionary classification** can be quite useful in the study of living organisms; for instance, if scientists wish to know more about the basic biology of New World vultures, then they might start by learning what is known about the biology of storks, their closest relatives. And if bioprospectors want to look for new valuable biological compounds, they could start by investigating the chemicals found in relatives of organisms with already known valuable chemicals.

Developing Evolutionary Classifications. Evolutionary classifications are based on the principle that the descendant species of a common ancestor should share any biological trait that first appeared in that ancestor. For example,

(a) Old World vulture **(b)** New World vulture **(c)** Stork

Hooded Vulture (*Necrosyrtes monachus*) Turkey Vulture (*Cathartes aura*) Wood Stork (*Mycteria americana*)

Figure 12.18 The challenge of biological classification. (a) Old World vulture; (b) New World vulture; and (c) stork. The evolutionary relationship between New World vultures and storks is not evident from their appearance.

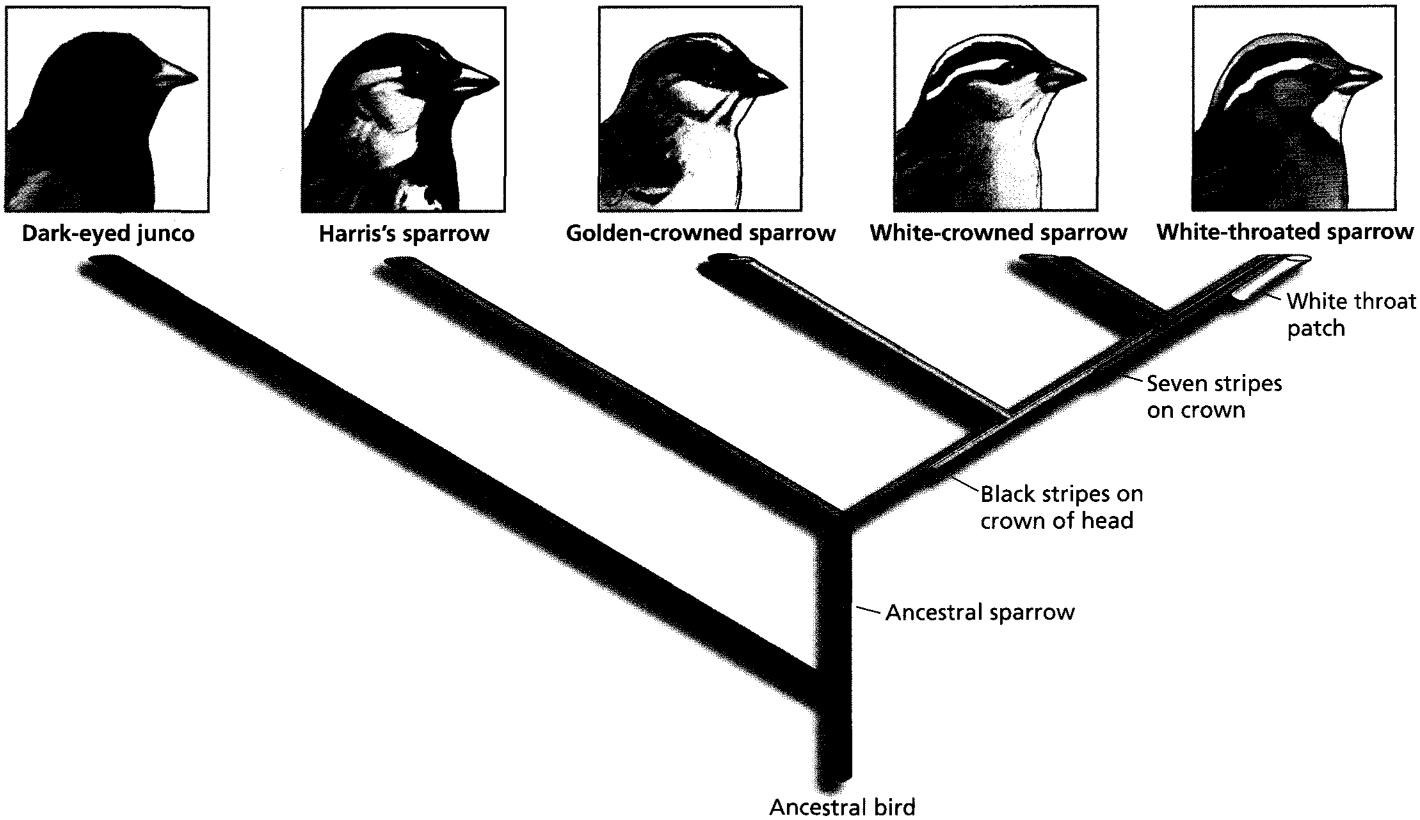


Figure 12.19 Reconstruction of an evolutionary history. The relationships among these four species of sparrow can be illustrated by their shared physical traits compared to a more distant relative, the dark-eyed junco. White-throated sparrows and white-crowned sparrows share a very distinct black-and-white head pattern, indicating that they are more closely related to each other than to golden-crowned sparrows, which have fewer stripes on their crowns. These three birds apparently share a more recent common ancestor with each other than with Harris's sparrow, however, which lacks crown stripes.

this principle has been used in an attempt to uncover the evolutionary relationship among different species of sparrow belonging to the genus *Zonotrichia*.

Figure 12.19 illustrates a hypothesized **phylogeny**—the evolutionary relationship—of species in the genus *Zonotrichia*. Scientists have used a technique called **cladistic analysis**, an examination of the variation in these sparrows' traits relative to a closely related species, to determine this phylogeny. For example, if we examine just the heads of the four sparrow species compared to their relative, the dark-eyed junco, we see that three—all but the Harris's sparrow—have dark and light alternating stripes on the crown of their heads. This observation seems to indicate that crown striping evolved early in the radiation of these sparrows. Among the three species with crown stripes, two have 7 stripes while the golden-crowned sparrow has only 3 stripes. An increase in the number of stripes appears to have evolved after the original striped crown pattern and contributes to the radiation among birds in this group. Finally, of the two species with 7 crown stripes, only one has evolved a white throat—the aptly named white-throated sparrow. In the case of these four sparrows, it appears that every step in their radiation involved a visible change in their appearance. A phylogeny of humans produced in a very similar way is presented in Chapter 9.

Unfortunately, reconstructing evolutionary relationships is not as simple as the sparrow example suggests. Descendant species may lose a trait that evolved in their ancestor, or unrelated species may acquire identical traits via convergent evolution, as described in Chapter 11. You can even see convergence in the phylogeny in Figure 12.19; golden-crowned sparrows, like the white-throated species, have a patch of golden feathers on their heads that appears to have evolved independently. The existence of convergent traits complicates attempts to determine the accurate evolutionary classification of organisms.

Testing Evolutionary Classifications. Any classification developed by a biologist can be considered a hypothesis of the evolutionary relationship among organisms. It is difficult to test this hypothesis directly—scientists have no way of observing the actual evolutionary events that gave rise to distinct organisms. However, scientists *can* test their hypotheses by using information from both fossils and living organisms. By examining the fossils of extinct organisms, scientists can gather clues about the genealogy of various groups. For example, fossils of vulture-like birds clearly indicate that this lifestyle evolved independently in both the Old World and the New World.

Information from living organisms can provide an even finer level of detail about evolutionary relationships. As illustrated earlier in Figure 12.5, closely related species should have similar DNA. If the pattern of DNA similarity matches a hypothesized evolutionary relationship among species, the phylogeny is strongly supported. This is the case with the hypothesized relationship between New World vultures and storks; DNA sequence comparisons indicate that the DNA of New World vultures is more similar to the DNA of storks than it is to that of Old World vultures. These data allow scientists to strongly infer that New World vultures are closely related to storks and that their similarities to Old World vultures are a result of convergent evolution. In contrast, DNA sequence comparisons do not support the sparrow phylogeny presented in Figure 12.19. Here, the data suggest that white-crowned birds and golden-crowned birds are closely related, and white-throated sparrows are a more distant relative. In this case, more observations are needed to discern the true evolutionary relationships among the *Zonotrichia*. In Chapter 9 we described multiple supportive tests of another phylogeny—in that case, the evolutionary relationship among humans and apes.

The examples of phylogeny reconstruction and testing as described here and in Chapter 9 provide nice illustrations of the process, but the species they employ are not likely to contain biological molecules that are valuable to humans. The evolutionary reconstructions that bioprospectors are most interested in are those performed on groups of species that already contain valuable members. For instance, relatives of the curarine-producing curare vine are likely to contain similar secondary biochemical pathways that produce slightly different muscle relaxants. Once a hypothesis of evolutionary relationship *is* reasonably well supported by additional data, bioprospectors can use the information gathered about one species in a classification group to predict the characteristics of other species in that group. This helps them to identify related species that could be additional sources of biological gold.

Although an evolutionary classification of groups that are likely to contain valuable chemicals would probably increase the speed of discovery, the current slow pace of reconstructing and testing phylogenies means that bioprospectors do not always have this information. Some bioprospectors have turned to the humans who have the most intimate knowledge of the usefulness of organisms in their environments—healers in cultures that extensively use their natural landscapes as sources of medicines.

Learning from the Shamans

To this point, we have been describing the search for biologically active compounds in living organisms as a process of scientific exploration whereby bioprospectors "discover" new compounds from nature. This is true for organisms in Yellowstone's hot springs; chemicals derived from these organisms were probably truly unknown to humans. For many other species, however, people have known of their usefulness for thousands of years. This knowledge is maintained in the traditions of indigenous people in biologically diverse areas, people who use native organisms as medicines, poisons, and foods. In many cultures, the repository of this traditional knowledge is the medicine man or woman. A shaman, as aboriginal healers are often called, can help direct bioprospectors to useful compounds by teaching about their culture's traditional methods of healing. Shamans employ many remedies that are highly effective against disease. Several bioprospectors have consulted with shamans to increase their chances of finding useful drugs (Figure 12.20).

Figure 12.20 Indigenous knowledge. This shaman of the Matses people of the Amazon rain forest is collecting plants for use in medicines. His intimate knowledge of the natural world is the product of the long history of his people in this diverse environment.

Using the knowledge of native people in developing countries to discover compounds for use in wealthy, developed countries is highly controversial. This process is often referred to as **biopiracy** because organisms and active compounds discovered by traditional healers can be patented in the United States and Europe, potentially providing enormous financial rewards to the bioprospector with no return to a shaman or his people. The United Nations Convention on Biodiversity has sought to alleviate biopiracy by asserting that each country owns the biodiversity within its borders. However, because the U.S. government has not signed this legally binding document, companies in the United States are not required to abide by its terms. Additionally, even when a country makes a bioprospecting agreement with a pharmaceutical firm, it is unlikely that the indigenous community within the country will benefit in any way from a new drug developed from its store of knowledge. Indigenous peoples recently have begun questioning the ethics of bioprospecting via shamans, and several proposed agreements between developing countries and pharmaceutical firms have come under criticism.

The bioprospecting agreement between Diversa and Yellowstone National Park has not escaped charges of biopiracy. While Diversa is not relying on information from indigenous people to help locate valuable organisms, critics have charged that the managers of Yellowstone are essentially "selling off" organisms and chemical compounds that belong to the American public. In addition, they argue that the action of bioprospecting itself will damage the very resource that provides these remarkable discoveries. The federal courts have dismissed lawsuits against Yellowstone National Park and Diversa that address these points according to current law, but the issue remains an ethical dilemma: What is the responsibility of individuals and corporations profiting from biological diversity to the source and survival of that diversity?

Biological diversity represents an enormous resource for humans, but it also comes with an awesome responsibility. Actions of the U.S. Congress protected Yellowstone National Park and perhaps ultimately enabled the discovery of *Thermus aquaticus* and *Taq* polymerase. But thousands of useful organisms are lost every year through the destruction of native habitat, and our ability to use these organisms is diminished by the loss of indigenous cultures and their shamans. The dramatic rate of biodiversity loss not only denies humans still-undiscovered biological molecules but also diminishes Earth's ability to sustain our population and robs future generations of the diverse wonder and beauty of nature that our generation may be the last to truly enjoy. Chapter 14 discusses the causes, consequences, and possible solutions for the current biodiversity crisis. Humans can help to reduce the rate at which biodiversity is being lost but only if we begin to appreciate the value of the diversity that surrounds and sustains us.

CHAPTER REVIEW

Summary

12.1 Biological Classification

- Bioprospectors seek to discover new drugs and other useful chemicals from the diversity of living organisms on Earth (p. 318).
- The number of known living species is estimated to be between 1.4 and 1.8 million, but the total number of species may be as high as 100 million (p. 319).
- Organisms are classified in domains according to evolutionary relationships and in kingdoms based on similarities in structure and lifestyle (pp. 320–322).

Web Tutorial 12.1 The Tree of Life

12.2 The Diversity of Life

- Life on Earth began about 3.5 billion years ago with simple prokaryotes, but it would be 1.5 billion years before eukaryotes evolved (p. 323).
- Bacteria and Archaea are prokaryotes, simple single-celled organisms without a nucleus or other membrane-bound organelles. They are abundant, found in a variety of habitats, and rely on a variety of food sources. Prokaryotes may produce antibiotics or have chemicals that function in extreme conditions (pp. 323–324).
- Eukaryotes, cells with nuclei and other membrane-bound organelles, probably evolved from symbioses among ancestral eukaryotes and prokaryotes (p. 325).
- The kingdom Protista is a hodgepodge of organisms that are typically unicellular eukaryotes. Algae are protists that are especially interesting to bioprospectors because they make defensive chemicals against predators and produce unique food-storage compounds (pp. 325–327).
- Multicellular organisms did not appear until approximately 600 million years ago, and this advance in form led to the diversity of species on Earth today (p. 328).
- Animals are motile, multicellular eukaryotes that rely on other organisms for food. Animal groups evolved in a short period of time known as the Cambrian explosion. Bioprospectors are interested in animals that produce venom or defensive chemicals (pp. 328–330).
- Fungi are immobile, multicellular eukaryotes that rely on other organisms for food and are made up of thin, threadlike hyphae. Fungi often produce antibiotics that kill their competitors, and some can escape detection by their living host's immune system (pp. 331–332).
- Plants are multicellular, photosynthetic eukaryotes. They have become increasingly adapted to land habitats over time. The diversity of flowering plants may be due partly to their production of defensive chemicals (pp. 332–334).

Web Tutorial 12.2 Endosymbiotic Theory

12.3 Learning About Species

- Some bioprospectors look for useful products by screening as many compounds as possible against a particular disease (pp. 337–338).
- An understanding of the ecological relationships of organisms provides clues to the likelihood and nature of possible chemical compounds in organisms (p. 338).
- Determining the evolutionary relationships among living organisms can help provide clues about an organism's traits. Phylogenies are created and tested by evaluating the shared traits of different species that indicate they shared a recent ancestor (pp. 339–340).
- Studying how indigenous healers called shamans use organisms can help bioprospectors identify species that may have useful chemicals (p. 341).
- Biopiracy occurs when a small group of people benefit from the knowledge of an indigenous culture; this practice may also undermine society's efforts to protect biodiversity (p. 341).

Learning the Basics

1. What characteristics of flowering plants may have driven the diversification of this group of organisms?
2. How is knowledge of the ecology of an organism useful for predicting what types of valuable chemicals it may possess?
3. How are hypotheses about the evolutionary relationships among living organisms tested?
4. Which of the following kingdoms or domains is a hodgepodge of different evolutionary lineages?

   A. Bacteria; **B.** Protista; **C.** Archaea; **D.** Plantae; **E.** Animalia
5. Comparisons of ribosomal RNA among many different modern species indicate that ________________.

   A. there are two very divergent groups of prokaryotes;
   B. the kingdom Protista represents a conglomeration

of very unrelated forms; **C.** fungi are more closely related to animals than to plants; **D.** a and b are correct; **E.** a, b, and c are correct

6. Which of the following characteristics distinguishes prokaryotes from eukaryotes?

   A. Eukaryotes have a nucleus, while prokaryotes do not.; **B.** Prokaryotes lack ribosomes, which are found in eukaryotes.; **C.** Prokaryotes do not contain DNA, but eukaryotes do.; **D.** Eukaryotic organisms are much more widespread than prokaryotes.; **E.** Prokaryotes produce antibiotics, and eukaryotes do not.

7. The mitochondria in a eukaryotic cell ______________.

   A. serve as the cell's power plants; **B.** probably evolved from a prokaryotic ancestor; **C.** can live independently of the eukaryotic cell; **D.** a and b are correct; **E.** a, b, and c are correct

8. Most animals ______________.

   A. are insects; **B.** lack a backbone; **C.** are still unidentified; **D.** a, b, and c are correct; **E.** b and c are correct

9. Fungi feed by ______________.

   A. producing their own food with the help of sunlight; **B.** chasing and capturing other living organisms; **C.** growing on their food source and secreting chemicals to break it down; **D.** filtering bacteria out of their surroundings; **E.** producing spores

10. Phylogenies are created based on the principle that all species descending from a recent common ancestor ______________.

    A. should be identical; **B.** should share characteristics that evolved in that ancestor; **C.** should be found as fossils; **D.** should have identical DNA sequences; **E.** should be no more similar than species that are less closely related

Analyzing and Applying the Basics

1. Unless handled properly by living systems, oxygen can be quite damaging to cells. Imagine an ancient nucleated cell that ingests an oxygen-using bacterium. In an environment where oxygen levels are increasing, why might natural selection favor a eukaryotic cell that did not digest the bacterium but instead provided a "safe haven" for it?

2. Imagine you have found an organism that has never been described by science. The organism, made up of several hundred cells, feeds by anchoring itself to a submerged rock and straining single-celled algae out of pond water. What kingdom would this organism probably belong to, and why do you think so?

3. Imagine two fungi. Both weigh the same; however, one consists of a few short, very thick hyphae, and the other consists of many long, thin hyphae. Can they both absorb the same amount of food? If not, which fungus is more effective?

Connecting the Science

1. Scientists initially ridiculed the hypothesis that eukaryotic cells evolved from a set of cooperating independent cells. Most biologists still believe that competition for resources among organisms is the primary force for evolution. Do you think biologists' dismissal of the role of cooperation in evolution is a reflection of how life really "works," or do you think that it is a function of scientists' immersion in a culture that values competition over cooperation? Explain your choice.

2. Do we have an obligation to future generations to preserve as much biodiversity as possible, considering that many organisms may contain currently unknown "biological gold"? Would simply preserving the information contained in an organism's genes (in a zoo or other collection) be good enough, or do we need to preserve organisms in their natural environments?