# CHAPTER 16

# The Origin and Evolution of Microbial Life: Prokaryotes and Protists

## Objectives

**Introduction** Describe the formation of stromatolites and explain the significance of the organisms that produce them.

### Early Earth and the Origin of Life

**16.1** Describe the conditions under which the first life likely formed and the nature of those first living organisms.
**16.2** Describe the timing and likely events that led to the origin of life on Earth.
**16.3** Describe the experiments of Dr. Stanley Miller and their significance in understanding how life might have first evolved on Earth.
**16.4** Explain the potential role of clay particles in the early evolution of life on Earth.
**16.5** Describe the roles of RNA in the early evolution of life on Earth.
**16.6** Describe the nature of the first cooperative associations of molecules enclosed by membranes.

### Prokaryotes

**16.7** Describe the history and diverse roles of prokaryotic life.
**16.8** Compare the characteristics of Bacteria and Archaea.
**16.9** Compare the different shapes of prokaryotes.
**16.10** Describe the nutritional diversity of prokaryotes.
**16.11** Describe the diverse types of Archaea living in extreme environments.
**16.12** Describe the structures and functions of the diverse features of prokaryotes.
**16.13** Explain the nature and causes of "blooms" of growth in ponds and lakes.
**16.14** Describe some of the diseases associated with bacteria.
**16.15** Describe Koch's postulates and explain their significance to science.
**16.16** Describe the history of bioterrorism and the effectiveness of anthrax as a weapon.
**16.17** Describe the important positive natural roles and human uses of prokaryotes.

### Protists

**16.18** Explain how the first eukaryotic cells likely originated as a community of prokaryotes.
**16.19** Describe the basic types of protists. Explain why biologists think that they represent many kingdoms.
**16.20** Describe the characteristics of the four most common groups of protozoa.
**16.21, 16.22** Describe and compare cellular slime molds and plasmodial slime molds.
**16.23, 16.24** Describe the characteristics of algae, including seaweeds. Compare dinoflagellates, diatoms, and green algae.

**16.25** Explain how multicellular life may have evolved from protists.
**16.26** Create a short timeline noting the first evolution of multicellular life and the first movement of life onto land.

## Key Terms

stromatolite
ribozyme
RNA world
Bacteria
Archaea
peptidoglycan
coccus
bacillus
autotroph
photoautotroph
chemoautotroph
heterotroph
photoheterotroph
chemoheterotroph
extreme halophile
extreme thermophile
methanogen
prokaryotic flagellum
pilus
endospore
actinomycete
cyanobacterium
pathogen
exotoxin
endotoxin
Lyme disease
Koch's postulates
bioremediation
membrane infolding
endosymbiosis
symbiosis
protist
protozoan
flagellate
amoeba
pseudopodium
apicomplexan
ciliate
cellular slime mold
plasmodial slime mold
plasmodium
alga
dinoflagellate
diatom
green alga
brown alga
kelp
red alga
multicellular green algae
alternation of generations
gametophyte
sporophyte

## Word Roots

**chemo-** = chemical; **hetero-** = different (*chemoheterotroph:* an organism that must consume organic molecules for both energy and carbon)

**endo-** = inner, within (*endotoxin:* a component of the outer membranes of certain gram-negative bacteria responsible for generalized symptoms of fever and ache)

**exo-** = outside (*exotoxin:* a toxic protein secreted by a bacterial cell that produces specific symptoms even in the absence of the bacterium)

**gamet-** = a wife or husband (*gametophyte:* the multicellular haploid form in organisms undergoing alternation of generations, which mitotically produces haploid gametes that unite and grow into the sporophyte generation)

**halo-** = salt; **-philos** = loving (*halophile:* microorganisms that live in unusually highly saline environments such as the Great Salt Lake or the Dead Sea)

**photo-** = light; **auto-** = self; **-troph** = food, nourish (*photoautotroph:* an organism that harnesses light energy to drive the synthesis of organic compounds from carbon dioxide)

**pseudo-** = false; **-podium** = foot (*pseudopodium:* a cellular extension of amoeboid cells used in moving and feeding)

**sporo-** = a seed; = **-phyto** = a plant (*sporophyte:* the multicellular diploid form in organisms undergoing alternation of generations that results from a union of gametes and that meiotically produces haploid spores that grow into the gametophyte generation)

**stromato-** = something spread out; **-lite** = a stone (*stromatolite:* rocks made of banded domes of sediment in which are found the most ancient forms of life)

# Lecture Outline

**Introduction** *How Ancient Bacteria Changed the World*

A. The evolution of life has had a profound effect on the Earth.
   1. Photosynthetic prokaryotes (cyanobacteria) evolved very early in the history of life and left unique fossilized communities as **stromatolites.**
   2. Modern-day cyanobacteria of this type, less common because of predation, are virtually indistinguishable from the early forms found in stromatolites (Figure 16.0).
   3. In addition to being the ancestors of today's cyanobacteria, these first photosynthetic cyanobacteria produced the Earth's first oxygen-rich atmosphere.
   4. Photosynthetic prokaryotes were dominant for about 2 billion years, from nearly 3 billion years ago (bya) to about 1 bya.
   5. This chapter begins a survey of all of Earth's life forms in an evolutionary context, beginning with the evolution of life itself.
      *NOTE:* The earliest organisms were ancestors of modern prokaryotes. They and the first eukaryotes (early protists) have inhabited our planet for a much longer time than have members of any other kingdom. Through the evolutionary events that resulted in their great diversity, all existing metabolic reactions evolved, at least in an early form.

## I. Early Earth and the Origin of Life

**Module 16.1** Life began on a young Earth.

A. The age of the universe is estimated to be between 10 and 20 billion years old, while Earth coalesced from gathering interstellar matter about 4.5 bya.

B. The first atmosphere was likely to have been dominated by hot hydrogen gas. However, the Earth's gravity was not strong enough to hold onto the light $H_2$.

C. Studies of modern volcanoes suggests that the Earth's second early atmosphere was composed of water vapor, carbon monoxide, carbon dioxide, nitrogen, and possibly some methane and ammonia.

D. Earth's crust cooled and solidified about 4.1 bya, condensing water vapor into early seas. The early Earth was also subject to intense lightning, volcanic activity, and ultraviolet radiation (Figure 16.1A).
   *NOTE:* It is ironic that life arose under conditions that included bombardment by UV radiation and now a major environmental concern is the depletion of the ozone layer that protects the planet from this radiation (Modules 7.14 and 38.3).

E. Fossil evidence shows that photosynthetic prokaryotes existed by 3.5 bya (Figures 16.1B, D).
   *NOTE:* The immensity of geological time and the very early events discussed can be made more meaningful by putting them in perspective. Borrowing an idea used by many, use a geologic time scale divided into a "life-on-Earth year." On such a scale, prokaryotic life evolves in mid-March, eukaryotes first appeared around September 1, dinosaurs flourished around Christmas, and the typical human life span of 70 years is represented by the last half-second on December 31.

F. Because cyanobacterial photosynthesis is complex and advanced, the first cells likely evolved earlier, perhaps as early as 3.9 bya (Figure 16.1C).

**Module 16.2** How did life originate?

A. Early ideas on the origin of life held that life arose by spontaneous generation.

B. Experiments in the 1600s showed that larger organisms couldn't arise spontaneously from nonliving matter.

C. In the 1860s, French scientist Louis Pasteur confirmed that all life today, including microbes, arises only from preexisting life. However, Pasteur's experiments did not deal with the question of the origin of life.

D. It is very likely that life on Earth arose between 4.1 and 3.5 bya.

E. Most biologists subscribe to the hypothesis that the earliest life forms were simpler than any that exist today, and that they evolved from nonliving matter.

F. Although extraterrestrial organic molecules could have seeded Earth's early environment, most scientists think that life arose from nonorganic molecules present in Earth's early oceans and atmosphere.

G. A possible scenario: Organic monomers evolved first, then polymers, then aggregates that eventually formed in the particular arrangement that allowed simple metabolism and self-replication. Data supporting the likelihood of many of these steps exist from a number of experiments.
*NOTE:* The following modules detail some of the experimental evidence and theory supporting the steps in this scenario. No one has completed all the steps in order. Today's environment (even in laboratories) is very different from the environment of the early Earth. Huge amounts of time are needed for these complex developments to occur.

**Module 16.3** Talking About Science: Stanley Miller's experiments showed that organic molecules could have arisen on a lifeless Earth.

A. In the 1920s, Oparin and Haldane proposed that organic chemistry could have evolved in the early Earth's environment because it contained no oxygen and was reducing.

B. An oxidizing environment (like Earth's $O_2$-rich environment today) is corrosive, tending to break molecular bonds. Thus, life could not spontaneously arise today on Earth.

C. A reducing environment tends to add electrons to molecules, building more complex forms from simple ones.

D. In 1953, Dr. Miller tested this hypothesis using an artificial mixture of inorganic molecules ($H_2O$, $H_2$, $CH_4$, and $NH_3$) in a laboratory environment that simulated conditions on the early Earth (Figure 16.3A, B).

E. Within days, the mixture produced amino acids, some of the 20 amino acids that are found in organisms today (see Module 3.12).

F. More recent experiments, using modifications of Miller's setup to more closely mimic the early Earth's environment (less $H_2$, $CH_4$, and $NH_3$ and more $CO$, $CO_2$, and $N_2$), have produced all 20 naturally occurring amino acids, sugars, lipids, and nitrogenous bases of nucleotides.

G. Rather than the early atmosphere, many scientists think that deep-sea vents and submerged volcanoes provided the chemicals required for the origin of life.

**Module 16.4** The first polymers may have formed on hot rocks or clay.

A. *Review:* Polymerization occurs by dehydration synthesis (Module 3.3).

B. Although biological polymerization occurs enzymatically in organisms today, the reactions can also occur when dilute solutions of monomers are dripped on hot mineral surfaces (heat forces the dehydration synthesis) or on clays (electric charges concentrate monomers, and metallic atoms act as catalysts).

C. American biochemist Sidney Fox has made polypeptides from mixtures of amino acids dripped on hot mineral surfaces.

**Module 16.5** The first genetic material and enzymes may both have been RNA.

A. *Review:* The flow of genetic information from DNA to RNA to protein is intricate and probably did not evolve as such (see Module 10.15).

B. The essential difference between cells and nonliving matter is replication.

C. A number of lines of reasoning and some experiments support the hypothesis that the first genes may have been made of RNA. Short RNA molecules can assemble spontaneously, without cells or enzymes, from precursor nucleotides. Some of these sequences will self-replicate if placed with additional monomer nucleotides. Further, some RNAs can act as enzymes **(ribozymes),** even one that catalyzes RNA polymerization (Figure 16.5; Module 10.10).

D. The hypothetical period in the evolution of life, when RNA played the role of both genetic material and enzyme, is termed the **RNA world.**

**Module 16.6** Molecular cooperatives enclosed by membranes probably preceded the first real cells.

A. Life requires the close and intricate cooperation of many different polymers. Macromolecules may have cooperated prior to the development of membranes (Figure 16.6A).

B. Experimental evidence shows that polypeptides and lipids self-assemble into microspheres, fluid-filled droplets with semipermeable, membranelike coatings. Though not alive, these microspheres grow by the attraction of additional polypeptides or lipids and divide when they reach a certain maximum size (Figure 16.6B).

C. Early molecular cooperation may have involved a primitive form of translation of polypeptides directly from genes in RNA. If these cooperating molecules were incorporated into a microsphere, the basic structures for self-replicating cells would be present (Figure 16.6C).

D. At this point, a primitive form of natural selection would favor those molecular co-ops that were most efficient at growing and replicating.

## II. Prokaryotes

**Module 16.7** Prokaryotes have inhabited Earth for billions of years.

*Review:* Prokaryotic cells (Module 4.4).

A. Fossil evidence shows that prokaryotes were abundant 3.5 bya, and they evolved alone for the following 1.5 billion years.

B. Prokaryotes are ubiquitous, numerous, and small, surviving in environments that are too hot, cold, acidic, salty, or alkaline for any eukaryote (Figure 16.7).

C. Despite being small, prokaryotes influence all other life—as the cause of disease and other problems, as benign inhabitants of all environments, and, more commonly, in beneficial relationships with all other living things.

D. Probably the most essential activities carried out by prokaryotes are the numerous ways they function in the decomposition of the dead remains (cellular and molecular) of other organisms.

**Module 16.8** Archaea and Bacteria are the two main branches of prokaryotic evolution.

*NOTE:* When viewed through a microscope, these two groups look similar.
*Review:* Classification of prokaryotes is first discussed in Module 15.14.

A. The main differences between these two groups are summarized on Table 16.8. Many of these differences concern their nucleic acids (rRNA sequences, RNA polymerase, and the presence of introns).

B. Other differences between **Archaea** and **Bacteria** concern the structure of their cell walls and cell membranes.

C. In most features archaea are more similar to eukaryotes than to bacteria.

D. *Review:* Currently, it is thought that modern archaea and eukaryotes evolved from a common ancestor (Figure 15.14B).

**Module 16.9** Prokaryotes come in a variety of shapes.

A. **Cocci** (singular, *coccus*) are spherical and often occur in defined groups of two or more (Figure 16.9A). Those that occur in clusters are called staphylococci. Those that occur in chains are called streptococci.

B. **Bacilli** (singular, *bacillus*) are rod-shaped and usually occur unaggregated (Figure 16.9B). Diplobacilli occur in pairs and streptobacilli occur in chains.

C. Vibrios resemble commas (Figure 16.9C).

D. Spirilla and spirochetes are spiral-shaped. Spirilla are shorter and less flexible than spirochetes (Figure 16.9D).

**Module 16.10** Prokaryotes obtain nourishment in a variety of ways.

A. *Review:* Cellular respiration (Chapter 6) and photosynthesis (Chapter 7).

B. Modes of nutrition refer to how organisms obtain energy and carbon (Table 16.10).

C. **Autotrophs** are "self-feeders" that make carbon compounds from the carbon in $CO_2$ and the energy in sunlight **(photoautotrophs)** or inorganic compounds such as hydrogen sulfide **(chemoautotrophs).**
*Preview:* Chemoautotrophic prokaryotes living in hydrothermal vents are discussed in the introduction to Chapter 34.

D. Cyanobacteria are photoautotrophic prokaryotes that use $H_2O$ as a source of electrons and release $O_2$ as a waste product.

E. **Heterotrophs** are "other-feeders" that make carbon compounds from the carbon in existing organic compounds and obtain energy from those same compounds **(chemoheterotrophs)** or from sunlight **(photoheterotrophs).**

F. *E. coli* is an important chemoheterotroph that lives in the human intestine, that can live on simple sugars alone (Figure 16.10).

G. With generation times as short as several hours or less, prokaryotic populations can multiply exponentially as long as there is a ready supply of nutrients.

H. There are two hypotheses regarding the evolution of nutrition.

   1. The first hypothesis is that chemoheterotrophs obtained the necessary carbon and energy from the rich soup of ions and molecules in which they evolved.

   2. The second hypothesis is that chemoautotrophs obtained the carbon from dissolved $CO_2$ and the energy from chemical reactions involving sulfur, iron, and deep-sea hydrothermal vents.

**Module 16.11** Archaea thrive in extreme environments—and in the ocean.

A. **Extreme halophiles** thrive in salty places such as the Great Salt Lake (Figure 16.11A).

B. Some **extreme thermophiles** thrive in hot springs, even at temperatures above boiling (for example, deep-ocean vents). Other extreme thermophiles thrive in very low pH environments such as those found in Yellowstone National Park (Figure 16.11B).

C. The **methanogens** are a group of anaerobic, methane-producing bacteria that thrive in some vertebrate intestines and in the mud of swamps.

D. Methanogens are the organisms responsible for the production of marsh gas and are a major contributor to flatulence in humans. Methanogens also digest cellulose in the gut of animals such as cattle and deer.

E. Archaea are turning up in environments that are not so extreme. They are found at all depths in the ocean and are in equal proportions to bacteria at depths below 1000 meters. More research needs to be conducted on this new domain.

**Module 16.12** Diverse structural features help prokaryotes thrive almost everywhere.

A. *Review:* The size, structure, and function of **prokaryotic flagella** differ from those aspects of eukaryotic flagella (Module 4.18).

B. Flagella can be either scattered over a cell or in bunches at one or both ends. They are composed of protein in two parts: external, nonmembrane-bounded filaments and rotating rings embedded in the plasma membrane and cell wall. Motion is produced as they spin on their axes like propellers. (Figure 16.12A)

C. *Review:* The role of sex pili in conjugation (Module 12.2).

D. **Pili** are protein filaments thinner than bacterial flagella (Figure 16.12B). Pili help bacteria stick to each other or to surfaces in their environments.

E. Some bacteria can survive adverse environmental conditions by producing thick-walled **endospores** inside the parent cell walls around a replicated copy of DNA (Figure 16.12C). Endospores are extremely resistant to decomposition and disintegration.

F. An example of the toughness of endospores is illustrated by those of *Clostridium botulinum,* a bacterium that grows in anaerobic, low-acid environments, such as poorly canned vegetables. The toxin released by colonies of this bacterium causes botulism when consumed by humans.

G. **Actinomycetes** are constructed from branching filaments of cells. They are chemoheterotrophic soil bacteria that break down organic molecules. Some actinomycetes are commercial sources of antibiotics (for example, streptomycin from *Streptomyces* bacteria; Figure 16.12D).

**Module 16.13** Connection: Cyanobacteria sometimes "bloom" in aquatic environments.

A. Blooms are population explosions of microorganisms.

B. Large blooms of **cyanobacteria** indicate polluted water conditions (Figure 16.14A, B). Such blooms often indicate pollution by organic wastes, such as phosphates and nitrates, from agricultural runoff.
*NOTE:* Blooms of cyanobacteria can release large amounts of toxins that kill fish. Blooms of all sorts of microorganisms can use up $O_2$ during night-time respiration and suffocate other $O_2$-requiring organisms. Relate the information in this module to the material presented in Chapter 38 concerning the human impact on the biosphere.

C. The lake pictured in Figure 16.13A may look very much like the conditions in which cyanobacteria dominated ($\approx$3.0 bya to 1.5 bya).

D. The photosynthetic apparatus of these cyanobacteria may be very similar to that which first released oxygen into Earth's atmosphere.

**Module 16.14** Connection: Some bacteria cause disease.

A. Bacterial **pathogens** cause about half of all known human diseases and are responsible for diseases in all other eukaryotes.

B. Diseases can be caused by bacterial growth on, and destruction of, tissues, but they are more likely to be caused by the release of **exotoxins** (exotoxins are made of glycolipids) from growing bacteria or the presence of **endotoxins** on the surfaces (cell walls) of these bacteria.

C. *Staphylococcus aureus* is a normal skin bacterium, but when it grows inside a person, the exotoxins it produces can cause serious disease, such as toxic shock syndrome (Figure 16.14A).

D. Harmless bacteria can develop pathogenic strains. For example, *E. coli* O157:H7, normally found in cattle, produce an exotoxin that causes bloody diarrhea and may even lead to kidney failure. The best prevention is to avoid undercooked meat.

E. Species of *Salmonella* produce endotoxins that cause food poisoning and typhoid fever.

F. Sanitation, the use of antibiotics, and education are three of our defenses against bacterial diseases.

G. However, antibiotic-resistant bacteria have evolved and are now a major health issue (Module 13.22).

H. The cause of **Lyme disease,** *Borrelia burgdorferi,* is carried by a tick and elicits a distinctive set of symptoms and potential disorders (Figure 16.14B).

**Module 16.15** Connection: Koch's postulates are used to identify disease-causing bacteria.

A. Discovering the cause of disease is the first step in preventing or curing the disease.

B. In 1876, Koch presented diagnostic criteria proving *Bacillus anthracis* to be the cause of anthrax:

1. The same pathogen must be found in each host.
2. The pathogen must be isolated into pure culture.
3. The original disease must be produced in new hosts inoculated with the culture.
4. The same pathogen must be isolated again from the new host (Figure 16.15B).

C. *Review:* **Koch's postulates** provide a good example of the process of science (Module 1.2).

D. For some pathogens, Koch's postulates cannot be used because the organism cannot be cultured outside the host. The cause of syphilis, the spirochete *Treponema pallidum,* is such an organism, but the first postulate is true, and other evidence leaves no doubt that this bacterium is the cause of the disease.

**Module 16.16** Connection: Bacteria can be used as biological weapons.

A. Use of biological organisms as weapons have played a part throughout history. Victims of bubonic plague (the causative agent of which is *Yersinia pestis*) were hurled into the ranks of opposing armies during the Middle Age of Europe. Other examples abound.

B. The United States started its own biological weapons program in 1943 and after developing high-quality bioweapons decided that the program was too repulsive to continue. The program was dismantled in 1969 and in 1975 the U.S. signed the Biological Weapons Convention that banned any future bioweapon programs.

C. The anthrax scare we experienced in the fall of 2001 was horrifying (five Americas died) yet it could have been worse. Anthrax is not as deadly as some other infectious diseases such as Ebola or smallpox. The route of infection determines the mortality rate. Cutaneous anthrax is relatively easy to treat, while pulmonary anthrax is treatable if detected early; however, it can be deadly because it is usually ignored as a common cold and then it's too late.

D. An anthrax vaccine is available for personnel in harm's way, military and foreign diplomats. Widespread vaccination programs would be too expensive and impractical. The solution is diplomacy.

**Module 16.17** Connection: Prokaryotes help recycle chemicals and clean up the environment.

A. Because of the variety of metabolic capabilities, prokaryotes play many beneficial roles in cycling elements among living and nonliving components of environments.

B. *Preview:* Chemical cycles are discussed more fully in Chapter 36.

C. Only prokaryotes are capable of nitrogen fixation, the conversion of $N_2$ gas to nitrogen in amino acids. Important nitrogen fixers include many cyanobacteria and many chemoheterotrophs in the soil.
*Preview:* Many plants depend on prokaryotes for nitrogen (Modules 32.13 and 32.14).

D. The breakdown of organic wastes by decomposers is one of the most common beneficial roles of prokaryotes.

E. Prokaryotic decomposers are part of the aerobic and anaerobic communities of organisms functioning in sewage-treatment plants (Figure 16.17A).

F. Natural bacteria are encouraged, or recombinant strains are used, to decompose away the remains of oil spills on beaches (Figure 16.17B).

G. Species of *Thiobacillus,* autotrophs that obtain energy from oxidizing ions in minerals, can be used to help remove toxic metals from old mine and industrial waste sites. However, their use in this role is limited since their metabolism adds sulfuric acid to the water.

## III. Protists

**Module 16.18** The eukaryotic cell probably originated as a community of prokaryotes.

A. The fossil record indicates that the first eukaryotes evolved more than 2.0 bya.

B. The endomembrane system is thought to have evolved by **membrane infolding** and resulted in the specialization of internal membranes into membrane-bounded organelles (Figure 16.18A), except mitochondria and chloroplasts.
*Review:* The endomembrane system is described in Modules 4.6–4.14.

C. **Endosymbiosis** is the likely basis of the origin of mitochondria and chloroplasts (Figure 16.18B), with mitochondria evolving first. The ancestral mitochondria may have been small heterotrophic prokaryotes and, similarly, the ancestral chloroplasts may have been small photosynthetic prokaryotes.

D. Several lines of evidence support the endosymbiotic hypothesis. Mitochondria and chloroplasts are similar in size and shape to prokaryotes and include bacterial-type DNA, RNA, and ribosomes. These organelles replicate in eukaryotic cytoplasm in a manner resembling binary fission. The inner, but not the outer, membranes of these organelles contain enzymes and electron transport molecules characteristic of prokaryotes, not eukaryotes.
*NOTE:* Endosymbiosis is common today between protists and/or prokaryotes.

**Module 16.19** Protists—unicellular eukaryotes and their close multicellular relatives—probably represent multiple kingdoms.

A. **Protists** are diverse and likely represent several kingdoms within Domain Eukarya.

B. As a group, protists are nutritionally diverse. Photosynthetic protists are referred to as "algae," a term with no taxonomic meaning. Heterotrophic protists are referred to as protozoans.

C. Colonial and multicellular protists whose immediate ancestors were unicellular are also considered protists.

D. Protists are found in all habitats but are most common in aquatic ones (Figure 16.19).

E. As eukaryotes, their cells are more complex than prokaryotes', with many kinds of organelles.

F. Evolutionarily, protists were pivotal because it was ancestral protists that evolved into ancestral plants, fungi, and animals.

G. Studies of protistan nucleic acid sequences provide evidence that suggests that these eukaryotic cells evolved from several different prokaryotic ancestors.

H. In the survey that follows, protists are considered by lifestyle, not by taxon.

**Module 16.20** Protozoa are protists that ingest their food.

A. Most species are free-living inhabitants of watery environments. A few are causes of dangerous diseases of humans and other animals. **Protozoa** are divided into four groups: **flagellates, amoebas, apicomplexans, ciliates.**
*NOTE:* Most protozoans have cells that lack cell walls, although some have relatively rigid protein skeletons below their plasma membranes.

B. Flagellates move by one or more flagella. *Giardia* is a flagellate that can cause abdominal cramps and severe diarrhea (Figure 16.20A.1). What makes *Giardia* particularly interesting is its two haploid nuclei and lack of mitochondria. The presence of vestiges of mitochondrial genes in its genome suggests that it once had mitochondria.

C. Another interesting flagellate is a species of *Trypanosoma* that is spread by tsetse flies and causes African sleeping sickness when it grows among blood cells. Trypanosomes escape a host's immune response by changing the molecular appearance of the proteins in the membranes (Figure 16.20A.2).

D. Amoebas move and feed by means of **pseudopodia** (Figure 16.20B).

E. Apicomplexans are all parasites, some causing serious human disease. *Plasmodium* species are spread by mosquitoes and cause malaria when they reproduce inside red blood cells (Figure 16.20C).
*Review:* The relationship between the sickle-cell allele and malaria (Module 9.14)

F. Ciliates are common, free-living forms that use cilia to move and feed. Daily activity is controlled by a polyploid macronucleus, and sexual recombination involves as many as 80 diploid micronuclei (Figure 16.20D).
*Review:* Cilia are defined as numerous, short, flagella-like structures arranged in more complex patterns than flagella (Module 4.18).

**Module 16.21** Cellular slime molds have both unicellular and multicellular stages.

A. The unicellular stage exists as individual, amoeboid cells that feed on bacteria in rotting vegetation, increasing their populations by mitotic cell division (Figure 16.21).

B. When their food supply runs out, the individual cells mass into a sluglike, multicellular colony.

C. The slugs wander about, moving to an advantageous location to reproduce. Some cells form a stalk below, and others form reproductive spores above.

D. Because they are eukaryotes with a simple developmental sequence, **cellular slime molds** have played a role in research on cellular differentiation.

E. Cellular slime molds have little in common with true molds.

**Module 16.22** Plasmodial slime molds form brightly colored "supercells" with many nuclei.

A. These protists exist in several different forms, including single cells, multinucleate feeding webs, resistant bodies, and multicellular reproductive structures.

B. They are common inhabitants of moist, rotting leaves and dead logs.

C. Life starts as individual amoeboid or flagellated cells (that can change back and forth, depending on the availability of water). As these cells ingest bacteria, they grow into an amoeboid plasmodium (a single undivided mass of protoplasm containing many nuclei) (Figure 16.22A).

D. When food runs out, the **plasmodium** mounds up into reproductive structures (Figure 16.22B).
*NOTE:* Because the nuclei in the feeding stage all divide by mitosis at exactly the same time, some **plasmodial slime molds** were used in early research on the chemistry of mitosis.

**Module 16.23** Photosynthetic protists are called algae.

A. Most **algae** have chloroplasts with chlorophyll *a,* as do plants (Module 7.6).
*NOTE:* The variety of accessory photosynthetic pigments causes many algae to be other colors than the typical grass-green color of chlorophyll *a.*

B. Some heterotrophic protists are considered algae.

C. The morphology of species varies considerably, from single cells to colonial filaments to plantlike bodies (seaweeds).

D. **Dinoflagellates** are uniquely shaped and move by two flagella in perpendicular grooves. Some dinoflagellates are responsible for toxin-releasing blooms in warm coastal waters that are known as red tides (Figure 16.23A). Nutritionally, some dinoflagellates are photoautotrophs, others chemoautotrophs, and others chemoheterotrophs.

E. **Diatoms** are unicellular, with uniquely shaped and sculptured silica walls. They are common components of watery environments (Figure 16.23B). In terms of being a food source, diatoms are to marine animals what plants are to land animals. Fossilized diatoms make up thick sediments of diatomaceous earth, which can be used either for filtering or as an abrasive.

F. The **green algae** are common inhabitants of fresh water and include a large variety of forms. Green algae share some features with higher plants and are considered to be either the plant kingdom's ancestors or members of the plant kingdom (Figure 16.23C).

**Module 16.24** Seaweeds are multicellular marine algae.

A. Seaweeds are the most complex of the photosynthetic protists. Some have complex bodies with leaflike, stemlike, and rootlike structures, all analogous rather than homologous to similar structures in higher plants.
*Review:* The difference between analogy and homology is discussed in Module 15.11.

B. Molecular and cellular studies suggest that there may be three groups of seaweeds; brown algae, red algae, and multicellular green algae are each placed in a different kingdom.

C. **Brown algae** include the most complex seaweeds. Some can grow to lengths of 100 m, forming **kelp** "forests" that are rich with other life (Figure 16.24A). Similarities of molecules used in photosynthesis suggest that brown algae and diatoms may be members of the same kingdom.

D. **Red algae** are most common in tropical marine waters. Most are soft-bodied, but encrusted species are important in building coral reefs (Figure 16.24B).

E. Some **multicellular green algae** are seaweeds, such as *Ulva.* The reproductive pattern of this alga involves alternation of generations, alternating between haploid **gametophytes** that give rise to gametes directly by mitosis and diploid **sporophytes** that give rise to spores by meiosis (Figure 16.24C).
*Preview:* An **alternation of generations** is found among many, but not all, algae and all plants and is important in understanding plant evolution (Module 17.4).

**Module 16.25** Multicellular life may have evolved from colonial protists.

A. Most multicellular organisms, including seaweeds, slime molds, fungi, plants, and animals, are characterized by the differentiation of cells that perform different activities within one organism.

B. Multicellularity undoubtedly evolved several times within the kingdom Protista. Some of these organisms evolved further into ancestors of the plant, fungus, and animal kingdoms.

C. A hypothetical scenario for the evolution of a multicellular plant or animal from an early protist is presented below:

1. Formation of ancestral colonies, with all cells the same.
2. Specialization and cooperation among different cells within the colony.
3. Differentiation of sexual cells from the somatic cells (Figure 16.25).

**Module 16.26** Multicellular life has diversified over hundreds of millions of years.

A. Through the use of fossil records and molecular techniques, the earliest multicellular organisms are thought to have been present on Earth about 1.2 billion years ago (Figure 16.26).

B. The fossil records indicate an abundance of multicellular organisms (red algae and invertebrate animals) dating from 600 to 700 mya. These organisms were red algae and animals resembling corals, jellyfish, and worms. Other kinds of multicellular algae probably existed as well, but their remains are yet to be found in the fossil record.

C. A mass extinction occurred between the Precambrian and Paleozoic eras.

D. Up until 500 mya to 475 mya, life was aquatic and represented by diverse animals and multicellular algae, along with ancestral protists and prokaryotes.

## Class Activities

1. Based on the information in the text (and additional outside sources if you so desire) ask your students to first consider the basis of the recognition of protists and then have them develop a phylogenetic tree of the protistan groups discussed in the text. Have them consider the question of whether or not the different types of seaweeds should be classified as protists.

## Transparency Acetates

| | |
|---|---|
| Figure 16.1C | Major episodes in the early history of life |
| Figure 16.3B | The synthesis of organic molecules in the Miller-Urey apparatus |
| Figure 16.5 | A hypothesis for the origin of the first genes |
| Figure 16.6A | The beginnings of cooperation among macromolecules in the absence of membranes |
| Table 16.8 | Differences between bacteria and archaea |
| Table 16.10 | Nutritional classification of organisms |
| Figure 16.12A | Prokaryotic flagella |
| Figure 16.15B | The usual procedure for demonstrating Koch's postulates |
| Figure 16.17A | The trickling filter system at a sewage treatment plant |
| Figure 16.18A | Infolding of a prokaryotic plasma membrane, giving rise to endoplasmic reticulum and a nuclear envelope |
| Figure 16.18B | Endosymbiotic bacteria giving rise to mitochondria and chloroplasts |
| Figure 16.24C | A multicellular green alga: *Ulva* (sea lettuce) and its life cycle |
| Figure 16.25 | A model for the evolution of a multicellular organism from a unicellular protist |
| Figure 16.26 | A timeline of early multicellular life |

## Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

| Animations and Videos | File Name |
|---|---|
| Prokaryotic Flagella (*Salmonella typhimurium*) Video | 16-12A-ProkFlagellaVideo-S.mov |
| *Oscillatoria* Video | 16-13B-OscillatoriaVideo-B.mov |
| *Oscillatoria* Video | 16-13B-OscillatoriaVideo-S.mov |
| *Euglena* Motion Video | 16-19-Euglena1Video-B.mov |
| *Euglena* Motion Video | 16-19-Euglena1Video-S.mov |
| *Euglena* Video | 16-19-Euglena2Video-B.mov |
| *Euglena* Video | 16-19-Euglena2Video-S.mov |
| *Amoeba* Pseudopodia Video | 16-20B-AmoebaPseud1Video-B.mov |

| | |
|---|---|
| *Amoeba* Pseudopodia Video | 16-20B-AmoebaPseud1Video-S.mov |
| *Amoeba* Video | 16-20B-AmoebaPseud2Video-B.mov |
| *Amoeba* Video | 16-20B-AmoebaPseud2Video-S.mov |
| *Stentor* Video | 16-20D-Stentor1Video-B.mov |
| *Stentor* Video | 16-20D-Stentor1Video-S.mov |
| *Stentor* Video | 16-20D-Stentor2Video-B.mov |
| *Stentor* Video | 16-20D-Stentor2Video-S.mov |
| *Vorticella* Cilia Video | 16-20D-Vorticella1Video-B.mov |
| *Vorticella* Cilia Video | 16-20D-Vorticella1Video-S.mov |
| *Vorticella* Detail Video | 16-20D-Vorticella2Video-B.mov |
| *Vorticella* Detail Video | 16-20D-Vorticella2Video-S.mov |
| *Vorticella* Habitat Video | 16-20D-Vorticella3Video-B.mov |
| *Vorticella* Habitat Video | 16-20D-Vorticella3Video-S.mov |
| Plasmodial Slime Mold Streaming Video | 16-22A-SlimeMoldStrVideo-B.mov |
| Plasmodial Slime Mold Streaming Video | 16-22A-SlimeMoldStrVideo-S.mov |
| Plasmodial Slime Mold Video | 16-22A-SlimeMoldVideo-B.mov |
| Plasmodial Slime Mold Video | 16-22A-SlimeMoldVideo-S.mov |
| Dinoflagellate Video | 16-23A-DinoflagellateVideo-B.mov |
| Dinoflagellate Video | 16-23A-DinoflagellateVideo-S.mov |
| Diatoms Moving Video | 16-23B-MiscDiatoms1Video-B.mov |
| Diatoms Moving Video | 16-23B-MiscDiatoms1Video-S.mov |
| Various Diatoms Video | 16-23B-MiscDiatoms2Video-B.mov |
| Various Diatoms Video | 16-23B-MiscDiatoms2Video-S.mov |
| *Volvox* Colony Video | 16-23C-VolvoxColonyVideo-B.mov |
| *Volvox* Colony Video | 16-23C-VolvoxColonyVideo-S.mov |
| *Volvox* Daughter Video | 16-23C-VolvoxDaughtrVideo-B.mov |
| *Volvox* Daughter Video | 16-23C-VolvoxDaughtrVideo-S.mov |
| *Volvox* Flagella Video | 16-23C-VolvoxFlagellaVideo-B.mov |
| *Volvox* Flagella Video | 16-23C-VolvoxFlagellaVideo-S.mov |
| *Chlamydomonas* Video | 16-24C-ChlamydomonasVideo-B.mov |
| *Chlamydomonas* Video | 16-24C-ChlamydomonasVideo-S.mov |

| **Activities and Thinking as a Scientist** | **Module Number** |
|---|---|
| Web/CD Activity 16A: *The History of Life* | 16.1 |
| Web/CD Thinking as a Scientist: *How Might Conditions on Early Earth Have Created Life?* | 16.3 |
| Web/CD Thinking as a Scientist: *What Are the Modes of Nutrition in Prokaryotes?* | 16.10 |
| Web/CD Activity 16B: *Prokaryotic Cell Structure and Function* | 16.12 |
| Web/CD Activity 16C: *Diversity of Prokaryotes* | 16.13 |
| Web/CD Thinking as a Scientist: *What Kinds of Protists Are Found in Various Habitats?* | 16.26 |