3.2 The Bacteria and Archaea: Tiny, Successful, and Abundant

When life arose on Earth more than 3.5 billion years ago, the first living organisms were tiny, single cells. The first modern lineage to arise—that is, the first to branch off the tree of life—was the Bacteria (Figure 3.2). Bacteria are probably most familiar as single-celled disease-causing organisms such as *Streptococcus pneumoniae* [noo-MO-nee-aye], which can cause pneumonia in humans. There is still uncertainty about this part of the tree of life, but one hypothesis suggests that the Archaea arose after the Bacteria, a scenario depicted by the evolutionary trees used in this book. Discovered in the 1970s, these single-celled, bacteria-like organisms are best known because some of them are extremophiles (literally, “lovers of the extreme”); they have been found thriving in boiling hot geysers, highly acidic waters, and the freezing cold seas off Antarctica. When the group Archaea arose, it split from the Eukarya lineage, which later gave rise to the rest of the world’s organisms.

Although they are distinct groups, Bacteria and Archaea are similar in both size (microscopic) and structure (single-celled); they are similar in many other ways as well. So it is appropriate that we begin our introduction to the major groups of life by describing them and their ways of life together.

Bacteria and Archaea are not only the simplest organisms, but also the most successful at colonizing Earth. They are quite variable in shape, with some having shapes like spheres (called cocci [cock-eye]; singular: coccus), rods (called bacilli [ba-SILL-eye]; singular: bacillus), or corkscrews (called spirochetes [SPI-ro-koets]); however, they all share a basic structural plan (Figure 3.3). The picture of efficiency, these stripped-down organisms are nearly always single-celled and small. They typically have much less DNA than the cells of organisms in the Eukarya have. Eukaryotic genetic material is often full of what appears to be extra DNA that serves no known function. In contrast, prokaryotic genetic material contains only DNA that is actively in use for the survival and reproduction of the bacterial cell. Prokaryotic reproduction is similarly uncomplicated: prokaryotes typically reproduce by splitting in two, a process called fission.

**Prokaryotes represent simplicity translated into success**

While most people think of biodiversity in terms of butterflies, redwood trees, and other complex organisms built of many cells, the vast majority of life on Earth is single-celled and prokaryotic. Scientists estimate that the number of individual prokaryotes on Earth is about $5,000,000,000,000,000,000,000,000,000,000,000$ or $5 \times 10^{30}$. Their success is due, in part, to how quickly they reproduce. Overnight, a single bacterium of the common species *Escherichia coli* (usually referred to by the abbreviation *E. coli*), which normally lives harmlessly in the human gut (see Figure 3.2), can divide to produce a population of 16 million bacterium.

Prokaryotes are also the most widespread of organisms, able to live nearly anywhere. They can persist even in places where most organisms would perish, such as the lightless ocean depths, the insides of boiling hot geysers, and miles below Earth’s surface. Because of their small size, prokaryotes also live on and in other organisms. Scientists estimate that 1 square centimeter of healthy human skin is home to between 1,000 and 10,000 bacteria.

In addition, while many prokaryotes need the gas oxygen to survive (that is, they are aerobes, from *aer*, “air”; “bios,” life), many others can survive without oxygen (they are anaerobes, from *ana*, “without”). This ability to exist in both oxygen-rich and oxygen-free environments also increases the number of habitats in which prokaryotes can persist. But the real key to the success of these groups is the great diversity of ways in which they obtain and use nutrients.

**Prokaryotes exhibit unmatched diversity in methods of obtaining nutrition**

Every organism needs two things to grow and survive: a source of energy and a source of carbon. Carbon is the chemical building block used to make critical molecules for living, such as proteins and DNA. Prokaryotes are distinguished by having the most diverse methods of obtaining energy and carbon of any group of organisms on Earth.

When humans and other animals eat, we consume other species, from which we get both energy (in the form of chemical bonds) and carbon (in the form of carbon-containing molecules). In fact, many organisms, including all animals, all fungi, and some protists, get their energy and carbon by consuming other organisms—what we normally would think of as eating. Prokaryotes can do the same. A familiar example is...
Clostridium botulinum [klaw-STRIED-ee-um BOTCH-00-LINE-um], a bacterium that causes food poisoning. It lives in and consumes food that humans have stored and produces a toxin that can make humans that eat that food sick. But while the rest of the world's eaters are restricted to consuming other organisms, or parts or products of other organisms, some prokaryotes can live by consuming carbon-containing compounds (such as pesticides) that are not parts of other organisms.

While animals, fungi, and many protists eat in order to live, plants and the remaining protists produce their own nutrition. These organisms get their energy from sunlight and their carbon from carbon dioxide, the gas that humans and other animals exhale, and use the two during photosynthesis to produce sugars. Some prokaryotes carry out photosynthesis as well. Cyanobacteria [sigh-AN-oh-... ] (also called blue-green algae, although they are not algae), which make up the green slime more commonly known as pond scum, are a familiar example of prokaryotes that use sunlight and carbon dioxide to make their own nutrients (Figure 3.4).

But while the Eukarya can only eat or carry out photosynthesis, prokaryotes can also survive in two other ways. Some prokaryotes can use light as an energy source, the way plants and organisms such as cyanobacteria do, but instead of getting their carbon from carbon dioxide, they derive it from organic compounds. Finally, there are prokaryotes that use carbon dioxide as a carbon source, as plants and cyanobacteria do, but get their energy from such unlikely materials as iron and ammonia (Figure 3.5).
Prokaryotes can thrive in extreme environments

Prokaryotes are well known for living in nearly any kind of environment. While some bacteria thrive in unusual environments, Archaea is the group best known for the extreme lifestyles of some of its members. Some are extreme thermophiles (thermo, “heat”; phile, “lover”) that live in geysers and hot springs. Others are extreme halophiles (halo, “salt”), thriving in high-sodium environments where nothing else can live—for example, in the Dead Sea and on fish and meat that have been heavily salted to keep most bacteria away (Figure 3.6).

Not all archaeans, however, are so remote from daily experience. Members of one group, the methanogens (methano, “methane”; gen, “producer”), inhabit animal guts and produce the methane gas in such things as human flatulence (intestinal gas) and cow burps.

Prokaryotes play important roles in the biosphere and in human society

Because they are able to use such a variety of food and energy sources and to live under such wide-ranging conditions, prokaryotes play numerous and important roles in ecosystems and in human society. For example, plants require the chemical nitrate, which they cannot make themselves. For this they depend on bacteria that can take nitrogen, a gas in the air, and convert it to nitrate. Without these bacteria there would be no plant life, and without plant life there would be no life on land.

Like plants, some bacteria, such as cyanobacteria, can photosynthesize. (Photosynthesis will be covered in detail in Chapter 8.) This ability makes them producers, the organisms at the base of food webs. Other bacteria are important decomposers. Oil-eating bacteria can be used to clean up ocean oil spills. Bacteria that can live on sewage are used to help decompose human waste so that it can be safely, usefully returned to the environment. Bacteria also live harmlessly in animal guts (including our own), aiding in food digestion.

Of course, not all prokaryotes are helpful. Many bacteria cause diseases; some are the source of nightmares, such as the flesh-eating bacteria able to destroy human flesh at frightening rates. With their ability to use almost anything as food, bacteria can also attack crops, stored foods, and domesticated livestock.

Bacteria and Archaea exhibit key differences

While similar in many ways, the Bacteria and Archaea are distinct lineages. In recent years, biologists have learned more about the Archaea, the more recently recognized of the two groups. One key distinction shows up in their DNA: much of archaean DNA is unique to archaeans. The Archaea and Bacteria also differ in how their metabolism (cellular machinery) is run. In addition, there are specific structural differences in the cells of the two groups: most prokaryotic cells have both a cell wall and a plasma membrane (see Figure 3.3), but some molecules in those structures differ between the two groups.

3.3 The Protista: A Window into the Early Evolution of the Eukarya

Protista is the most ancient of the eukaryotic groups, making it the oldest kingdom within the Eukarya. Protista consists largely of single-celled eukaryotes, but contains some multicellular eukaryotes as well. Among the protists are some familiar groups, such as single-celled amoebas and kelp (which are multicellular algae), as well as many unfamiliar groups. One of the few generalizations that can be made about this hard-to-define group is that its members are diverse in size, shape, and lifestyle.

Much remains unknown about the evolutionary relationships of the protists. Figure 3.7 presents one hypothesis for the evolutionary tree of some of the major
The protists form a diverse group of single-celled and multicellular organisms. The evolutionary relationships among protist groups are poorly understood. For example, dinoflagellates, apicomplexans, and ciliates are shown branching off this evolutionary tree simultaneously, to indicate that the order in which these groups evolved is still unknown.

- Number of species discovered to date: ~30,000
- Functions within ecosystems: Producers, consumers, decomposers
- Economic uses: Kelp, a multicellular alga, is raised for food. However, protists are best known for the damage they do, causing red tides and diseases such as amoebic dysentery.
- Did you know? Malaria, the second most deadly disease after AIDS, is caused by *Plasmodium*, a protist.

Seaweeds, such as this sea lettuce, are among the most familiar protists, green algae, seen along coastal shores.

Single-celled dinoflagellates, like this one, can multiply rapidly, forming deadly red tides.

Diatoms are important producers in freshwater and marine environments. Their glasslike outer shells are microscopic works of art.

Animal-like organisms such as this Paramecium, a ciliate, swim using tiny hairlike structures called cilia.

An apicomplexan surrounded by red blood cells. This protist parasite, *Plasmodium*, causes malaria.
protist groups. Diplomonads are shown branching off first. Then three major groups—one including dinoflagellates, apicomplexans [ay-pee-kom-plex-uns], and ciliates; another including diatoms and water molds; and the last comprising the green algae—are shown splitting off at the same time. That is because scientists still do not know which of these three groups branched off first. Other protist groups are not shown on the tree because their placement is even more poorly understood.

Protists show great variety in their lifestyles. Some are plantlike; for example, green algae can photosynthesize, and plants are thought to have evolved from them. There are also animal-like protists—such as the ciliates—that move and hunt for food. Still others—such as the slime molds—are more like fungi. Most protists (such as Paramecium [pair-uh-MEE-see-um]; see Figure 3.7) are single-celled, but there are also many multicellular protists (such as kelp).

Protists represent early stages in the evolution of the eukaryotic cell

One of the most important events in evolutionary history was the evolution of eukaryotes. Unlike the cells of prokaryotes, the cells of the Eukarya contain internal compartments called organelles, which perform different functions. For example, the nucleus is the organelle that contains a eukaryotic cell’s DNA, and mitochondria [my-to-kon-dree-uh] (singular: mitochondrion) are organelles that produce energy for the cell. Where did these organelles come from?

Biologists hypothesize that eukaryotes arose when free-living prokaryotic cells engulfed other free-living prokaryotic cells. Scientists now believe that this engulfing happened many times in the history of life. The engulfing cells evolved into the Eukarya as, over time, the captured cells evolved into organelles. Organelles developed specialized functions, on which the eukaryotic cells housing them came to depend for survival; organelles also lost the ability to survive as free-living organisms. For example, plant cells today contain chloroplasts, the organelles that carry out photosynthesis. The chloroplast is thought to have originated from a cyanobacterium captured by another prokaryotic cell. Thus a combination of prokaryotes appears to have resulted in primitive eukaryotes, the group from which complex multicellular organisms evolved.

Protists are of particular interest because different protist groups illustrate the variety of experimentation in engulfment that has gone on over time. For example, Giardia lamblia belongs to the group known as the diplomonads. This protist lives in streams and other sources of fresh water. It results in a painful ailment of the digestive tract when consumed by humans, causing diarrhea and flatulence with a rotten-egg odor. Most single-celled eukaryotes contain a nucleus and one or more mitochondria, and chloroplasts if they photosynthesize. Giardia lamblia, however, appears to be a curious experiment in putting together a single-celled organism: it has two nuclei, no chloroplasts, and has lost the mitochondria it once had.

Protists provide insight into the early evolution of multicellularity

Some groups of protists are of interest to biologists because they have evolved from living as single-celled creatures to forming multicellular associations that function to varying degrees like more complex multicellular individuals. Among the more interesting of these experiments in the evolution of multicellularity are the slime molds, protists that were originally mistaken for molds (which are fungi). Commonly found on rotting vegetation, slime molds eat bacteria and live their lives in two phases: as independent, single-celled creatures and as members of a multicellular body. Like other protists that can live as either single-celled or multicellular organisms, slime molds are studied by biologists who hope to gain insight into the evolutionary transition from single-celled to multicellular living. The slime molds are among the protist groups excluded from the evolutionary tree in Figure 3.7 because their relationships to other protists remain poorly understood.

Protists had sex first

Protists provide insight into the early evolution of multicellularity

Protists were the group in which this form of reproduction first appeared, making sex one of its most noteworthy evolutionary innovations.

Protists are well known for their disease-causing abilities

Although most protists are harmless, many of the best-known protists are those that cause diseases. One example is the dinoflagellates (see Figure 3.7), a group of microscopic plantlike protists that live in the ocean and...
sometimes experience huge population explosions, known as blooms. Occasional blooms of toxic dinoflagellates cause dangerous “red tides.” During red tides, any shellfish that have eaten these toxic dinoflagellates will in turn be poisonous to humans eating the shellfish. The animal-like protist Plasmodium causes malaria, which kills millions of people around the world each year—more than any other disease except AIDS. Finally, protists left their mark on human history forever when one of them (often mistakenly referred to as a fungus) attacked potato crops in Ireland in the 1800s, causing the disease known as potato blight. The resulting widespread loss of potato crops caused a devastating famine and a major emigration of Irish people to the United States in the 1840s.

3.4 The Plantae: Pioneers of Life on Land

To some people, greenery means little more than salads and decorative houseplants. But plants are among evolution’s great pioneers. Life on Earth began in the water, where it stayed for 3 billion years. It was only when the Plantae—the plants—evolved from green algae that life took to land. In doing so, plants turned barren ground into a green paradise in which a whole new world of land-dwelling organisms, including ourselves, could then evolve.

Today the diversity of the Plantae—a kingdom within the domain Eukarya—ranges from the most ancient lineages—mosses and their close relatives—to ferns, which evolved next, to gymnosperms, and finally to the most recently evolved plant lineage, the angiosperms (Figure 3.8).

Life on land requires special structures

Figure 3.9 shows the basic structure of a plant. The key evolutionary innovation of plants is their ability to harvest chloroplasts in order to photosynthesize—to use light (energy from the sun) and carbon dioxide (a gas in the air) to produce food in the form of sugars. Most photosynthesis in plants takes place in their leaves, which typically grow in ways that maximize their ability to capture sunlight. A useful by-product of photosynthesis is the critical gas oxygen, which plants release into the air. Because plants are producers, they form the basis of essentially all terrestrial (land-based) food webs.

Organisms on land had to solve problems not faced by organisms living in the ocean. The most crucial of these was how to obtain and conserve water. One of the features allowing plants to do this is the root system, a collection of fingerlike growths that absorb water and nutrients from the soil. Another is the waxy covering over stem and leaves, known as the cuticle, which prevents plant tissues from drying out even when exposed to sun and air. A second challenge of life on land was gravity. While plants can float in water, they cannot “float” in the air. But plants cells have rigid cell walls. Composed of the organic compound cellulose, cell walls give the plant the rigidity it needs to grow up and into the air.

In addition to the features just mentioned, three major evolutionary innovations were critical to plants’ highly successful colonization of land: vascular systems, seeds, and flowers. Each of these innovations marks the rise of a separate major plant group.

Vascular systems allowed ferns and their allies to grow to great heights

Early in their evolution, plants grew close to the ground. Mosses and their close relatives, which make up the most ancient plant lineage, represent those early days in the history of plants. These plants rely on each cell being able to absorb water directly. Thus the innermost cells of their bodies receive water only after it has managed to pass through every cell between them and the outermost layer. Because such movement of water from cell to cell, like the movement of water through a kitchen sponge, is relatively inefficient, these plants cannot grow to great heights or sizes.

Ferns and their close relatives, the next major plant group to arise, were able to grow taller because they evolved vascular systems—networks of specialized tissues that extend from the roots throughout the bodies of plants (see Figure 3.9). Vascular tissues can efficiently transport fluids and nutrients, much as the human circulatory system of veins and arteries transports blood. In addition, the presence of water and other fluids in the vessels helps make the plant firmer; in the same way that a balloon filled with water is firmer than an empty balloon. By providing sturdiness and efficient circulation of water and nutrients, the evolutionary innovation of vascular systems allowed plants to grow to new heights and sizes. All plants, except mosses and their close relatives, have vascular systems.