Bacteria: The First Microbes

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This picture shows the hot spring Devil's Bath (Wai-O-Tapu Thermal Wonderland) in Rotorua, New Zealand. Thermal pools like this represent the harsh conditions under which the earliest of Earth's microorganisms evolved and flourished.

Looking Ahead

Bacteria are among the most successful organisms on Earth. Over the billions of years of their existence, they have evolved to occupy every conceivable niche on Earth; indeed, they influence almost everything we experience. In this chapter, we shall get to know the bacteria as we examine their structures and activities.

On completing this chapter, you should be able to . . .

- appreciate the enormous span of time in which bacteria have existed on Earth and understand their contributions to the formation of the world as we know it;
- summarize the various forms of known bacteria and define many of the submicroscopic structures associated with a bacterial cell;
- describe the process by which bacteria reproduce, and grasp the significance of the frequency of bacterial replication;
- identify some of the environments in which bacteria thrive, and recognize the different types of cultivation techniques available for growing bacteria in the laboratory;
- outline several important groups of bacteria in order to appreciate their diversity; and
- identify the importance of bacteria in the disease process and briefly summarize some of the mechanisms of bacterial disease and body resistance.

The Earth came into being an almost incomprehensibly distant 4.5 billion years ago. For the first several millions of years of its existence, Earth was a ball of molten rock. Then, as millennia passed, a thin crust formed over the hot core, and violent volcanic activity filled the days and nights. Now the Earth was awash with energy: There was radiation from the sun, lightning from intense electrical storms, and heat from radioactive decay and the ever-present volcanic eruptions. In the incessant rain and the tropically warm oceans, organic molecules were forming—amino acids, proteins, nucleotides, and carbohydrates—the stuff that one day would compose living things.

For its first billion years, the Earth was as barren of life as the surface of the moon is today. Then, about 3.5 billion years ago, microscopic cells, the first living things, came into being. Although scientists are uncertain how these cells arose, they are reasonably sure that these first life forms were bacteria. The ancient bacteria (like the modern forms) were tiny, single-celled creatures, with little evidence of internal structure. Organisms like these are called prokaryotes, a name that reflects the absence of a nucleus (*karyo* is Greek for "nut" [or nucleus], and *pro* means "primitive"). Chapter 2 compares prokaryotes and eukaryotes more fully.

- prokaryote A microorganism in the domain *Bacteria* or *Archaea* composed of single cells having a single chromosome but no cell nucleus or other membrane-bound compartments. *See also* eukaryote.
- eukaryote An organism whose cells contain a cell nucleus with multiple chromosomes, a nuclear envelope, and membrane-bound compartments.

Bacteria (or prokaryotes) were the only inhabitants of the Earth for over 2 billion years, nearly half of the planet's existence. Then, about 1.5 billion years ago, the eukaryotes evolved, as FIGURE 5.1 illustrates. These organisms, typified by protozoa, fungi, plants, and animals, have larger cells, with nuclei and complex internal structures. Although the eukaryotes were larger organisms, the bacteria were not threatened because by that time bacteria had the advantage—they were well-established and in full swing.

And what a group they were: Growing wildly in the oxygen-free atmosphere of Earth, the ancient bacteria chemically combined hydrogen with the carbon of carbon dioxide to form methane (not unlike what we find in a swamp today). Then the photosynthetic bacteria evolved. These forms are called cyanobacteria (or blue-green algae in the older literature). Cyanobacteria used their chlorophyll pigments in the process of photosynthesis to capture light energy and produce carbohydrates as energy-storage compounds. In so doing, they played a decisive role in Earth's development because photosynthesis dramatically increased the atmospheric concentration of oxygen from 1% to the current 21%. More than any other organisms on Earth, cyanobacteria were catalysts for the oxygen-based chemistry that now pervades earthly life.

- cyanobacterium (pl. cyanobacteria) An oxygen-producing, pigmented bacterium occurring in unicellular and filamentous forms that carries out photosynthesis.

All the contemporary bacteria developed from the evolutionary experiments that Mother Nature performed on these ancient forms. And the results have been spectacular, for modern bacteria have come to occupy every conceivable niche on Earth.

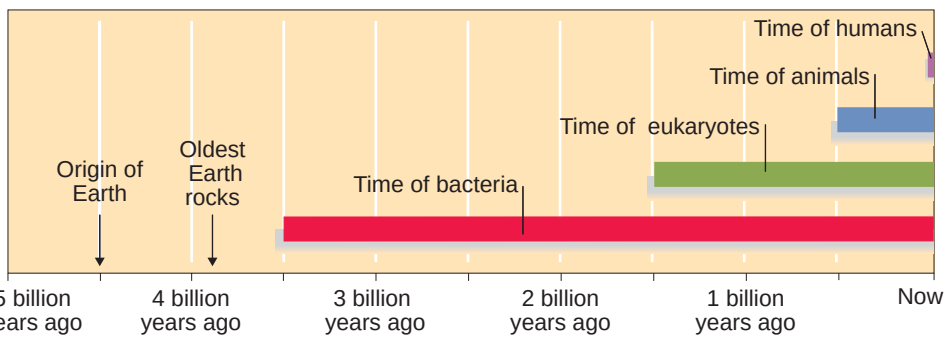


FIGURE 5.1 **The Bacteria on Earth.** This timeline shows how long various groups of organisms have existed on Earth. The bacteria have been in existence for a notably longer period of time than any other group, particularly humans. They have adapted well to Earth's varied conditions simply because they have had the longest opportunity to adapt.

Every crack, every crevice, every cranny—whether at the bottom of a 6-mile deep Pacific trench, at the pinnacle of Mount Everest, or in the blazing desert of the Sahara—contains some sort of bacterial life. A single pinch of rich soil contains over a billion bacteria. Indeed, a handful of that same soil contains more bacteria than all the people who have ever lived on planet Earth.

It should not be surprising that bacteria occupy a critical place in the web of life. Many bacterial species make major contributions to the mineral balance of the world by metabolizing the nutrients in freshwater, marine, and terrestrial environments. The bacteria residing in soil influence the Earth's ecology by breaking down the remains of all that die and recycling the elements. And certain bacterial species do what few other species of organisms on Earth can do—they trap nitrogen from the air and convert it to substances used by plants to make protein, which ultimately winds up on our plates as grains, meat, and dairy products.

In industrial and biochemical laboratories, bacteria are both workhorses and lab rats. Growing in enormous numbers in mammoth fermentation tanks, bacteria carry on their day-to-day chemical routines and yield products of substantial value. For example, they manufacture organic compounds; they produce fermented foods; they synthesize antibiotics and vitamins; and they serve as biological factories for genetic engineering. They even have a bearing on politics, as A Closer Look, below, explains.

Despite all the good they do, bacteria also pose a threat to humans because a small percentage of species cause infectious disease. Indeed, human history is replete with accounts of ravaging epidemics of cholera, plague, typhoid fever, and syphilis. But even as the great "slate-wipers" of history, bacteria may have served a useful purpose in giving the human population an opportunity to renew and improve itself. Some evolutionary biologists argue that bacteria are the key agents of natural selection for the human species; that is, in a sense, they help improve our species by selecting the fitter individuals through the distasteful task of infectious disease.

A CLOSER LOOK

Of Powder and Politics

The situation was quickly becoming desperate: It was 1915, Great Britain was at war with Germany, and the British supply of acetone was rapidly dwindling. Acetone is a solvent for making cordite, the powder used to make explosives for naval guns. Before the war, German industrial firms were major suppliers of acetone, but to expect any more shipments was unrealistic.

That year David Lloyd George, then Minister of Munitions, learned of the work of Chaim Weizmann and arranged to meet him. Weizmann, a Russian chemist living in England, was interested in bacterial fermentations. George explained the seriousness of the situation and told Weizmann that the usual wood distillation process was not working well enough to meet the demand for acetone. Weizmann's enthusiasm was fired; he resolved to do what he could.

Weizmann returned to his laboratory and worked relentlessly. Within a few weeks, he isolated an organism that transforms ordinary cornstarch into a mixture of acetone and other biochemicals. The organism was a bacterium belonging to the genus *Clostridium*. Weizmann reported his success to Lloyd George, and with the help of Canadian and American corporations, the process was scaled up to industrial proportions. By 1917, the British had their acetone, and cordite production resumed at full proportions.

Thirty-one years later, the state of Israel was created. Its first president was Chaim Weizmann.

As our constant companions, bacteria have impacted our lives in some ways that are clear and in some ways that have not yet been discovered. These remarkable and fascinating microbes are the subject matter of this chapter.

Bacterial Structure and Physiology

Bacteria differ structurally from all other kinds of organisms, which are the more complex eukaryotes. This difference was first noted in the 1950s with the development of the electron microscope and during studies into the biochemical and physiological properties of organisms. In very broad terms, a bacterium differs from a eukaryotic organism because it is much smaller and less complex. But, as we shall see in the pages to follow, the differences go much deeper.

General Morphology

- bacillus (pl. bacilli) (1) Any rod-shaped prokaryotic cell. (2) When referring to the genus *Bacillus,* it refers to an aerobic or facultatively anaerobic, rod-shaped, endospore-producing, gram-positive bacterial cell.
- coccus (pl. cocci) A spherical-shaped prokaryotic cell.
- spirochete A twisted bacterial rod with a flexible cell wall containing axial filaments for motility.
- spirillum (pl. spirilla) (1) A bacterial cell shape characterized by twisted or curved rods. (2) A genus of aerobic, helical cells usually with many flagella.

Bacteria generally occur in variations of three major forms. Rod-shaped bacteria are known as bacilli (sing., bacillus); other bacteria are spherical and are called cocci (sing., coccus); and still other bacteria have a long, spiral form and are known as spirochetes if the cells are rigid or spirilla (sing., spirillum) if they are flexible. FIGURE 5.2 summarizes these forms.

Species of bacilli vary in size, with the shortest ones measuring about 0.5 µm in length and the longer ones about 20 µm. However, there are extremes: In 1993, scientists from Indiana University discovered a bacterium of extraordinary size—600 µm long—in the gut of a surgeonfish. That record was surpassed in 1999, when a pearl-like bacterium approximately 750 µm in diameter was isolated from sediment samples obtained from the ocean floor off the coast of Namibia in Africa. To place its size in perspective, consider that this bacterium is roughly the size of the period at the end of this sentence. And, because a bacterium by definition is an invisible organism, the discovery of a visible bacterium may necessitate a reworking of the definition. (To be sure, one could argue that the phrase "visible bacterium" is what an English professor would call an oxymoron, two words that contradict each other.)

Cocci measure roughly 0.5 µm in diameter and occur in several configurations; that is, the bacteria may appear as diplococci (two cocci in a group) or as streptococci (cocci in a chain) or as tetrads (cocci in groups of four or eight). When cocci occur in random

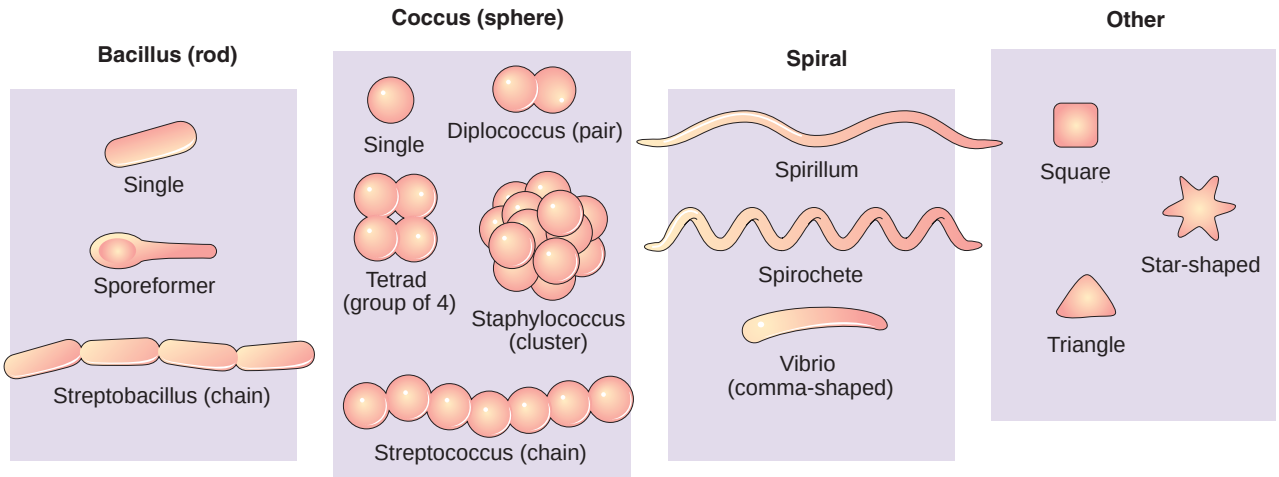


FIGURE 5.2 **Variations in Bacterial Structure.** The forms of bacterial species are variations of three general forms as well as a few miscellaneous forms.

clusters, the configuration is called a staphylococcus. This term is derived from the Greek word *staphyle,* which means "grape." The configuration can be important to identification of cocci. For instance, the bacterium that causes gonorrhea is a diplococcus, while the cause of "strep throat" is a streptococcus. The common "staph infection" is caused by a species of *Staphylococcus.* In medical labs, technicians can use a microscope to distinguish these configurations and assist physicians in their diagnoses.

■ staphylococcus (pl. staphylococci) (1) An arrangement of bacterial cells characterized by spheres in a grapelike cluster. (2) A genus of facultatively anaerobic, nonmotile, non-spore-forming, gram-positive spheres in clusters.

■ *Staphylococcus* staf-i-lō-kok'kus

Other forms exist as well. For example, cyanobacteria consist of elongated microscopic cells usually occurring in filaments, which may measure a meter or more in length. Although the cells are connected at their outer walls, each cell operates independently. Still other bacterial species we shall study later in this chapter have stalks and grow long, branching cells that develop complex structures at their tips.

Studying the structures of bacteria gives us an appreciation of their complexity and opens a window to their activities. It also helps us to realize that bacteria are much more than dots on a microscope slide. As we survey the structural makeup of bacteria, watch for the various functions that bacteria can perform. These functions give us a sense of their day-to-day existence.

Staining Procedures

Some microbes, such as protozoa and fungi, are usually large enough to be seen without staining, but almost all bacteria are too small. Moreover, bacterial cytoplasm is transparent, which adds to the difficulty of seeing bacteria. As early as the 1880s, scientists such as Robert Koch and Paul Ehrlich used stains to improve their ability to see bacteria. The basic notion underlying staining is that the chemical components of bacterial cytoplasm have an overall negative charge and attract stains such as crystal violet and methylene blue, which have a positive charge. Use of a single stain characterizes the so-called simple stain technique illustrated in FIGURE 5.3.

■ simple stain technique The use of a single cationic dye to contrast cells.

The Gram stain technique was developed in the 1880s by Christian Gram, a Danish physician. This technique has multiple steps and not only stains bacteria, but also separates them into two groups: the gram-positive bacteria and the gram-negative bacteria. The bacteria are first stained with crystal violet (see A Closer Look on page 93) and then with Gram's iodine solution. At this point, all the bacteria are purple. Now, the bacteria are washed with ethyl alcohol, and the gram-positive bacteria remain purple, but the gram-negative bacteria lose their color and become transparent. Then, in the final step, the pink dye safranin is applied to the bacteria. It stains the gram-negative bacteria (causing them to become pink), but it has no effect on the gram-positive bacteria (which remain purple). Microscopic observation reveals the color of the bacteria and tells us whether they are gram-positive or gram-negative.

■ Gram stain technique A staining procedure used to identify bacterial cells as gram-positive or gram-negative.

The Gram stain technique is called a differential technique, because it separates bacteria into two different groups. Knowing whether a bacterium is gram-positive or gram-negative is important because most bacterial species fall into one or the other group. Thus, Gram staining is a key first step in describing the characteristics of a bacterium. Certain antibiotics, such as penicillin, are effective against gram-positive bacteria but less so against gram-negative bacteria, and certain antiseptics and disinfectants affect gram-positive bacteria but not gram-negative bacteria (or vice versa). Other characteristics of these two groups are noted in other chapters.

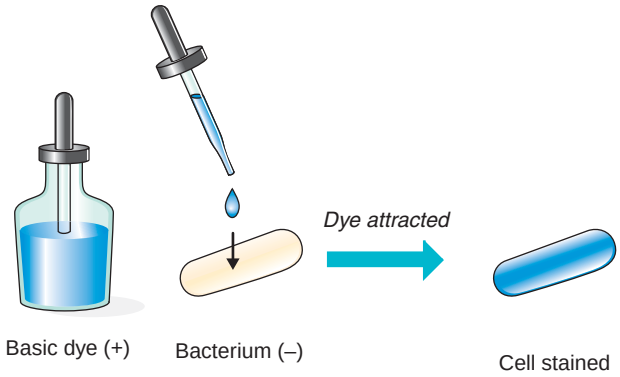
■ differential (stain) technique A procedure using two dyes to differentiate cells or cellular objects based on their staining.

Surface Structures

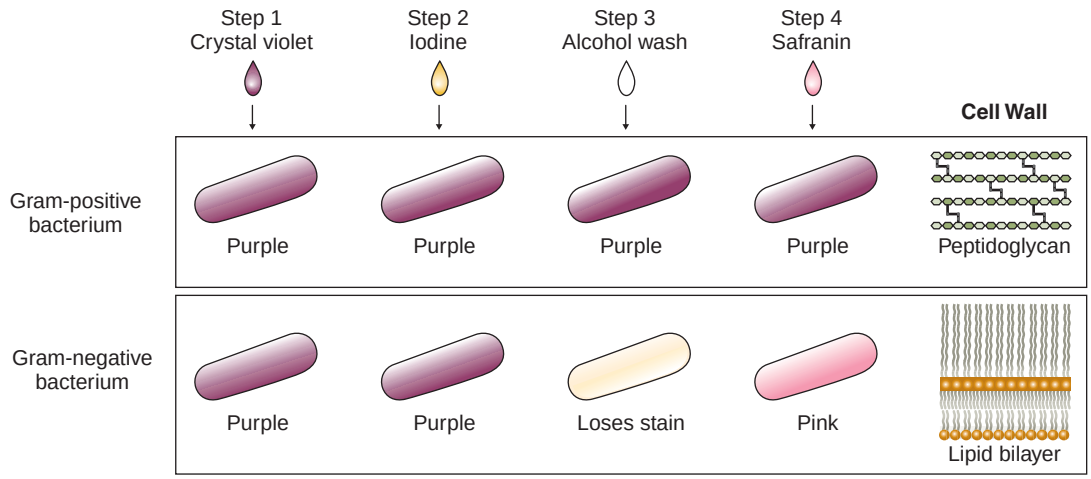
With certain exceptions, bacteria are encased in a cell wall. The cell wall contains a tough mesh of polysaccharide and protein called peptidoglycan. Peptidoglycan lends rigidity and strength to the cell wall and is found in no other living thing. Gram-positive bacteria have a thick layer of peptidoglycan in their cell walls (which may contribute to their ability to resist the alcohol wash used in Gram staining), while gram-negative bacteria

■ cell wall A carbohydrate-containing structure surrounding fungal, algal, and most prokaryotic cells.

■ peptidoglycan A complex molecule of the bacterial cell wall composed of alternating units of N-acetylglucosamine and N-acetylmuramic acid cross linked by short peptides.



(a) Simple stain technique



(b) Gram stain technique

FIGURE 5.3 **Stain Reactions in Microbiology.** (**a**) In the simple stain technique, the positively charged dye (+) is attracted to the negatively charged bacteria (–), and staining takes place. (**b**) The Gram stain technique is a differential procedure. All bacteria stain with crystal violet and iodine, but only gram-negative bacteria lose the purple color in the alcohol wash. Subsequently, these bacteria stain with the safranin dye. Gram-positive bacteria remain purple.

have a much thinner central peptidoglycan layer sandwiched between outer layers of other complex biochemicals.

The cell wall is the site of the bacterium's vulnerability to certain antibiotics, such as penicillin and its relatives (ampicillin, amoxicillin, methicillin, and numerous others). These antibiotics prevent the bacterium from synthesizing peptidoglycan, and they leave the microbe with only a cell membrane. Internal pressures soon cause the cell to swell and burst, as FIGURE 5.4 shows strikingly. Because gram-positive bacteria contain more peptidoglycan, these microbes are more susceptible to the effects of penicillin. Staphylococci and streptococci are examples of gram-positive bacteria sensitive to penicillin.

The structure of the bacterial cell membrane (also called the plasma membrane) is similar to its counterpart in eukaryotes. The essential feature is a double layer of phospholipids (a phospholipid bilayer) with protein molecules suspended in the phospholipids at the surface and spanning the layers. Some of these proteins function as enzymes during chemical reactions, and some transport substances across the cell membrane. Because of its ever-changing nature, the membrane is called a fluid mosaic. On the outside of the membrane, small carbohydrate molecules are linked to the

A CLOSER LOOK

"A.O. Means What?"

In modern bacteriology laboratories, the crystal violet dye used for Gram staining is prepared by mixing dye particles with a solution of a salt called ammonium oxalate. This procedure has not changed since 1929, when a graduate student named Thomas Hucker introduced it. How this "Hucker modification" came about is part of the folklore of microbiology.

Hucker was studying bacteriology at Yale University. Early in 1929, his advisor suggested that he contact several hospital and university laboratories to see how they were performing the Gram stain technique. Hucker was to report his findings in a presentation at an upcoming scientific meeting in Philadelphia. He dutifully sent out a series of letters and learned that the standard procedures were being used at all laboratories—all, that is, except Dartmouth's.

The reply from Dartmouth College piqued his interest. At the time, the usual procedure was to dissolve crystal violet in aniline oil. But Dartmouth bacteriologists apparently were using ammonium oxalate. Hucker tried ammonium oxalate and found that the stain improved with age and gave clearer results. He prepared his paper for the Philadelphia meeting and sent a draft to Dartmouth's biology department with a note of thanks. Soon thereafter he received a phone call from Dartmouth—they had never heard of ammonium oxalate for Gram staining. Hucker was perplexed.

In the days that followed, Hucker learned that a chemist had intercepted his survey letter and sent the reply. In writing out the method for preparing crystal violet, the chemist had read "A.O." on the bottle of Dartmouth's stain and assumed it meant that the dye was dissolved in ammonium oxalate. Aniline oil simply did not occur to him. Moreover, he had not bothered to check with the biology department because it was inventory time and other things were on his mind. Thus, a case of badly interpreted bacteriological shorthand led to the Hucker modification. Hucker became famous; the chemist remained anonymous.

■ glycocalyx A viscous polysaccharide material covering many prokaryotic cells to assist in attachment to a surface and impart resistance to desiccation.

proteins. The carbohydrates are believed to be recognition sites, where antibody molecules from the body's immune system unite with the bacteria during infection.

Gram-negative bacteria have a gap between the cell wall and the cell membrane. This gap is called the periplasmic space and is filled with material called periplasm. Research experiments performed in the 1990s indicate that this area is an active and important processing center. For example, organic nutrients too large to pass through the cell membrane are broken down in this space; peptidoglycan synthesis occurs here; and membrane constituents are conveyed through this space to their correct spots in the lipid layer.

Certain species of bacteria have a coating outside the cell wall called the glycocalyx; it is also known as a capsule if tightly bound to the cell, or a slime layer if slimy and flowing. The glycocalyx, shown in FIGURE 5.5, provides protection for the bacterium, shielding it from drying, chemicals, and environmental stresses. It should not be surprising that many species of pathogenic (disease-causing) bacteria have a glycocalyx.

Organic materials in the glycocalyx allow a bacterium to cling to surfaces. Glycocalyces are used, for example, by streptococci and other oral bacteria to bind to pockets between the teeth and gums as a prelude to dental caries. The bacteria break down the sugars and other carbohydrates we consume and produce large amounts of acid. Gradually the acid eats away at the enamel and forms a depression, or cavity. When the bacteria penetrate to the soft tissue below, they continue to multiply and often produce

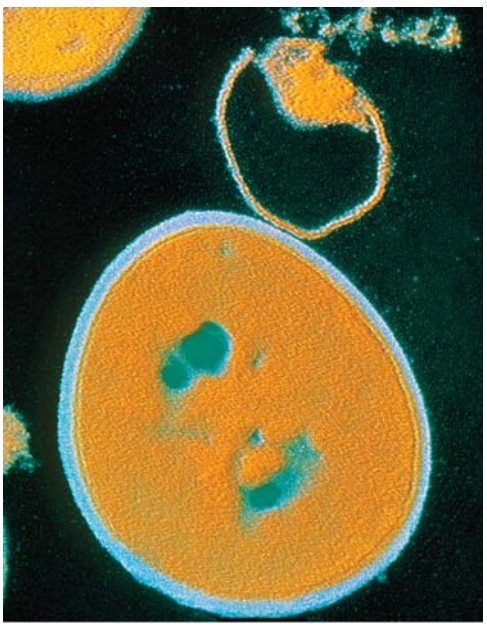


FIGURE 5.4 **The Effect of Penicillin.** A photomicrograph of a *Staphylococcus aureus* cell bursting after treatment with penicillin (×150,000). The antibiotic has prevented construction of the peptidoglycan layer of the cell wall, and internal pressures have led to weakening and disruption of the cell membrane.

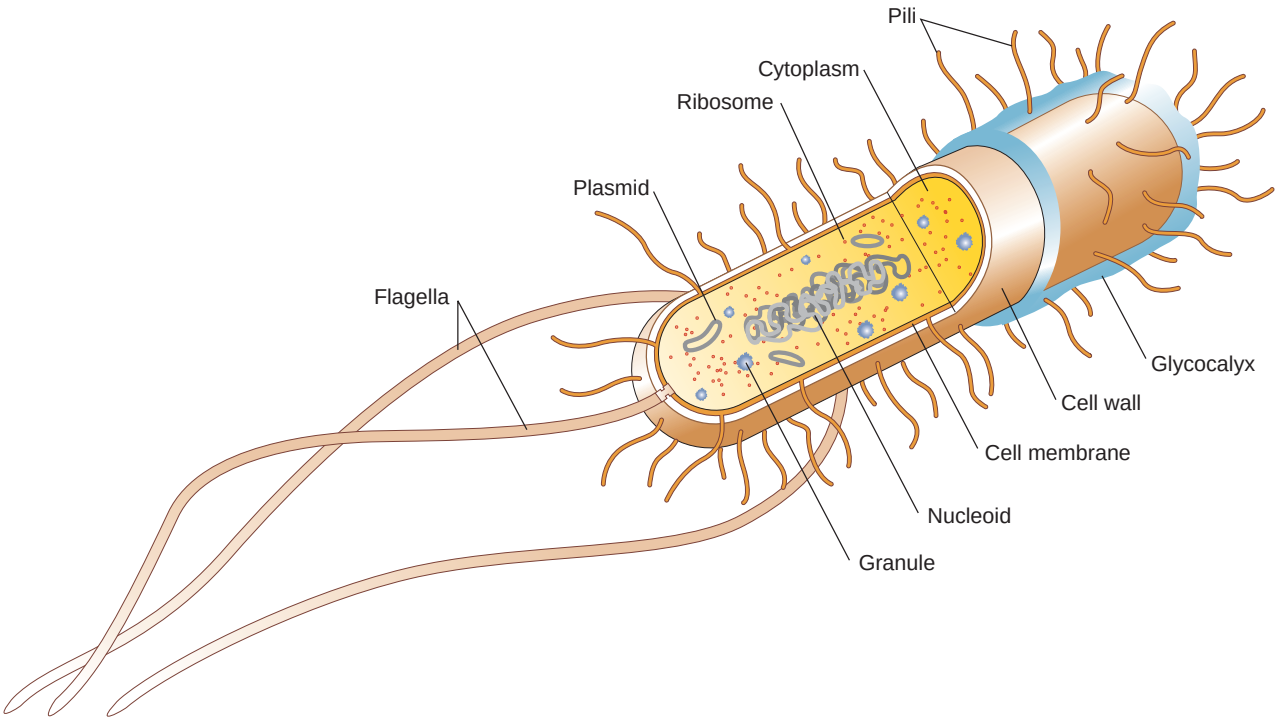


FIGURE 5.5 A Hypothetical Bacterial Cell. The structural features of this composite, "idealized" bacterium are drawn in a way that shows their relationships. Such a bacterium probably does not exist.

large amounts of gas. The gas presses against nerve endings and causes the throb we call a toothache. (When the dentist drills through to the infection site, the gas is released and the pain ebbs.)

■ flagellum (pl. flagella) A long, hair-like appendage composed of protein and responsible for motion in microorganisms; found in some bacteria, protozoa, algae, and fungi.

Bacteria may also contain hairlike structures anchored to the cell wall and cell membrane. One such structure, the flagellum, is a rigid filament of protein that rotates and propels a bacterium through its liquid surroundings. Various species of bacteria have a single flagellum, a tuft of flagella at one end of the cell, or flagella that cover their cell surface. A flagellum is too thin to be seen with the light microscope. However, it can be many times the length of the cell, as FIGURE 5.6 shows. Using flagella, bacteria appear to move in pulses along a series of curved lines (a "run") punctuated by

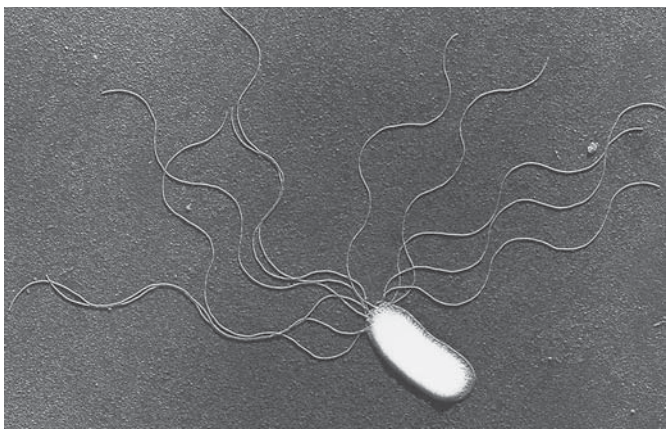


FIGURE 5.6 The Bacterial Flagellum. A transmission electron micrograph of *Pseudomonas marginalis* showing polar flagella (×38,800). Note that the flagella are many times the length of the bacterium and have a characteristic wavy arrangement.

periods of tumbling. A bacterium such as *E. coli* is capable of traveling about 2000 times its body length in an hour. Calculations for a 5-ft-10-in. human walking at about 2.25 miles per hour would yield about the same figure (which means there is at least one way in which humans and bacteria are equal).

Another hairlike structure called the pilus (pl., pili) helps bacteria attach to tissues or other surfaces. Pili are rigid cylindrical rods about 1 µm in length and about 7 nm thick. Each pilus consists of protein units wound in a helical (spiral) coil. When causing infection, bacteria use their pili to hold fast to the surfaces of the host cells. One novel approach to dealing with bacterial diseases is to synthesize drugs that will react with and neutralize the pili. A Closer Look below relates how research in this field is performed. Pili also help bacteria remain attached while they exchange genetic material, as we explore in Chapter 10.

■ pilus (pl. pili) A hairlike extension of the plasma membrane found on the surface of many bacteria and is used for cell attachment and anchorage. Some bacteria possess a specialized larger pilus (the F-pilus or conjugation pilus) that is used for conjugation; the passage of genetic information between bacteria.

Cytoplasmic Structures

The genetic information of bacteria is contained in a single chromosome occurring as a closed loop of deoxyribonucleic acid (DNA) in the cytoplasm. The DNA is tightly compacted and has no protein associated with it (in contrast to the DNA in eukaryotic cells). Because they have only one chromosome, bacteria are appealing as research tools in biochemical genetics—scientists can isolate the single chromosome and study its activity without worrying about the other chromosome in the pair, as they must do when working with eukaryotic cells. Also, there is no protein to interfere with their experiments, as happens when working with eukaryotic chromosomes. The cytoplasmic area

A CLOSER LOOK

Diarrhea Doozies

They gathered at the clinical research center at Stanford University to do their part for the advancement of science (and earn a few dollars as well). They were the "sensational sixty"—60 young men and women who would spend 3 days and nights and earn $300 to help determine whether hairlike structures called pili have a significant place in disease.

A number of nurses and doctors were on hand to help them through their ordeal. The students would drink a fruit-flavored cocktail containing a special diarrhea-causing strain of *Escherichia coli (E. coli)*. Thirty cocktails had *E. coli* with normal pili, and 30 had *E. coli* with pili mutated beyond repair. Bacteria with the threadlike pili should latch onto intestinal tissue and cause diarrhea, while those with mutated pili should be swept away by the rush of intestinal movements and not cause intestinal distress—at least that's what the sensational sixty were out to verify or prove false.

On that fateful day in 1997, the experiment began. Neither the students nor the health professionals knew who was drinking the diarrhea cocktail and who was getting the "free pass"; it was a double-blind experiment. Then came the waiting. Some volunteers experienced no symptoms, but others felt the bacterial onslaught and clutched at their last remaining vestiges of dignity. For some, it was 3 days of hell, with nausea, abdominal cramps, and numerous bathroom trips; for others, luck was on their side (investing in a lottery ticket seemed like a good idea at the time).

When it was all over, the numbers appeared to bear out the theory: The great majority of volunteers with mutated bacteria experienced no diarrhea, while the great majority of those with normal bacteria had attacks of diarrhea, in some cases, real doozies. All appeared to profit from the experience: The scientists had some real-life evidence that pili contribute to infection; the students made their sacrifice to science and pocketed $300 each; and the local supermarket had a surge of profits from sales of toilet paper, Pepto-Bismol®, and Imodium®.

nucleoid The chromosomal region of a prokaryotic cell.

where the bacterial chromosome concentrates is called the nucleoid. Thousands of genes, the functional units of DNA, make up the chromosome.

In addition to a chromosome, many bacterial species have tiny loops of DNA called plasmids. Suspended in the cytoplasm, the plasmids contain several genes that encode proteins for nonessential cell functions. Plasmids replicate independently of the chromosome and are important tools in modern DNA technology because they can be isolated, opened, and modified with new genes; the modified plasmids can then be inserted into fresh bacteria, where their new genes are activated to encode the protein desired by the biochemist. This imaginative and innovative process underlies much of the current revolution in biotechnology.

Bacteria also have in their cytoplasm the necessary structures for producing proteins and other substances essential to their existence. These include ribosomes (ultramicroscopic bodies consisting of RNA and protein), as well as transfer RNA molecules and a host of organic substances that make up the "body" of the cell. Included here are a variety of proteins, carbohydrates, lipids, and nucleotides. Numerous minerals and growth factors are included in the "living soup" of cytoplasm. The chemical activity going on in the cytoplasm is unceasing.

spore (1) A reproductive structure formed by a fungus. (2) A highly resistant dormant structure formed from vegetative cells in several genera of bacteria, including *Bacillus* and *Clostridium*.

Certain bacteria, particularly members of the genera *Bacillus* and *Clostridium,* have the ability to produce an extraordinarily resistant structure called the endospore. This structure, commonly known as the spore, is a unique form of the bacterium developed during its life cycle, generally when stress is encountered in the environment. The spore is formed during an involved process, illustrated in FIGURE 5.7. It contains a chromosome, two cell membranes, a cortex, a spore coat, and a surrounding wall called an exosporium. The spore's remarkable structure gives it the ability to withstand environmental stresses to the extent that it is probably the most resistant form of life known to science.

In 1995, California researchers led by Raul Cano reported the recovery of bacterial spores trapped in the intestine of a bee entombed in amber for 25 million years. Some scientists were skeptical that bacteria could remain alive as spores for 25 million years, but Cano's evidence was persuasive. Then, in 2000, West Chester University researchers reported recovering live *Bacillus* spores from New Mexico salt crystals 250 million years old (these spores were formed before dinosaurs walked the Earth). On a somewhat more practical level, bacterial spores of certain species can be boiled for 2 hours without destroying them, or they can be left in alcohol for 20 years. When placed in a nutritious environment, the spore walls crack open, and the spores revert to bacteria that reproduce and metabolize as if nothing had happened.

The ability of bacteria to form spores is key to certain types of bioterrorism. For example, *Bacillus anthracis,* the bacterium that causes anthrax, is a spore-former. The organism is easily grown in the laboratory, and its spores can be spread efficiently among large populations (for example, by releasing them in subway tunnels). Falling on the skin and inhaled into the lungs, the spores revert to vegetative (growing) bacteria that multiply furiously and within days cause extensive blood hemorrhaging and almost certain death unless antibiotic treatment is administered. Public health officials are constantly on guard to protect against this sort of biowarfare, and numerous popular novels are built around this topic. One such novel you might enjoy reading is *Rainbow Six* by Tom Clancy.

binary fission An asexual process in prokaryotic cells by which a cell divides to form two new cells while maintaining genetic constancy.

Bacterial Reproduction

Bacteria reproduce by the relatively straightforward method of binary fission, a process that results in a colony (or clone) of genetically identical cells. During binary fission, a mature bacterium increases in size, and its enzymes replicate its DNA to yield two

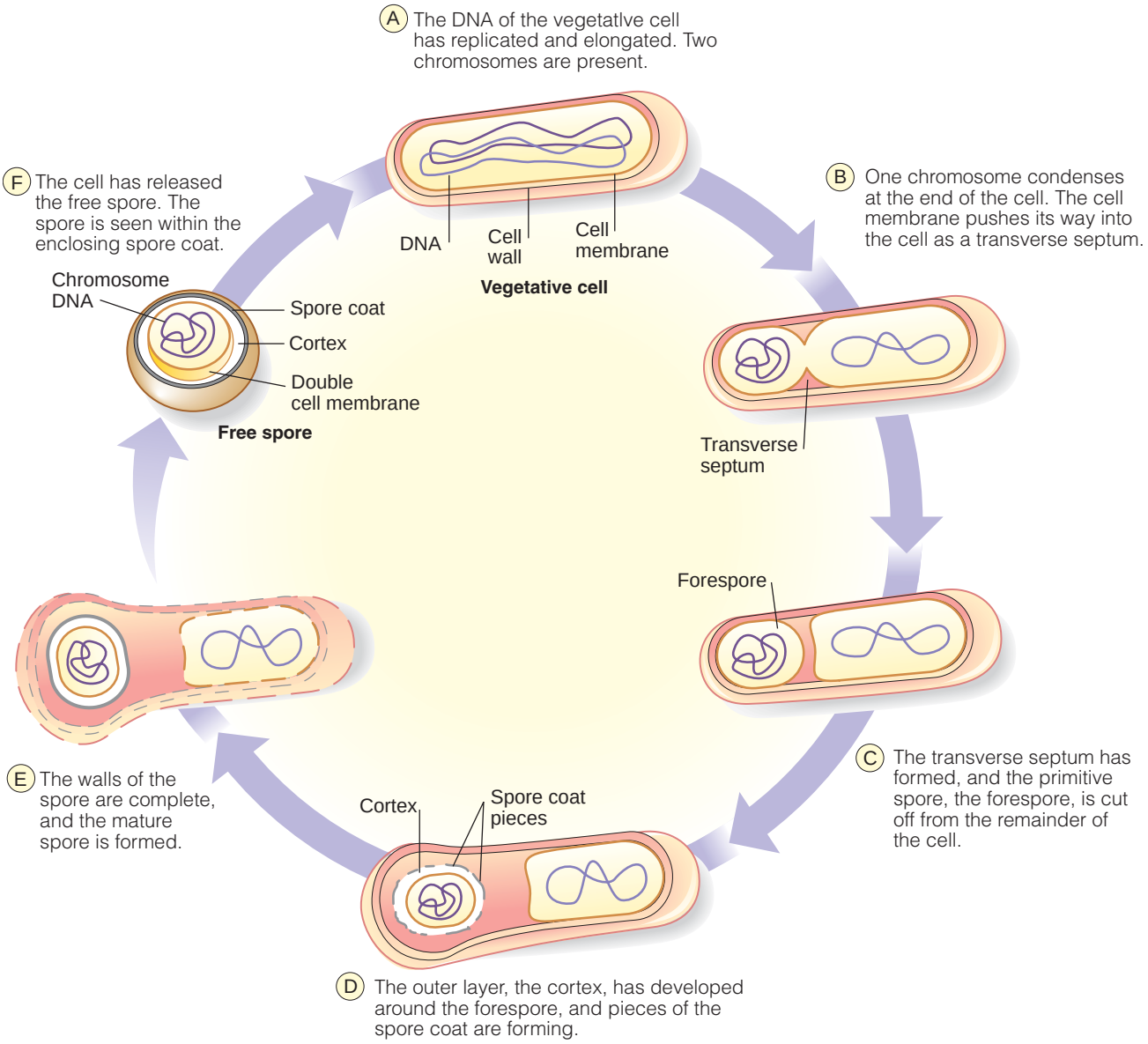


FIGURE 5.7 The Formation of a Bacterial Spore. The bacterial cell metabolizes nutrients and multiplies for many generations as a vegetative cell. After some time, the vegetative cell enters the sporulation cycle shown here and forms a free spore.

chromosomes. New cell wall and cell membrane grow inward from the margin of the cell, and as they come together, the two chromosomes separate, one into each compartment. (The effect is somewhat like forming two sausages from a single, long sausage.) The adjoining walls and membranes separate, and two new bacterial cells result. The entire process requires only a few seconds and is shown in FIGURE 5.8.

The method of bacterial reproduction is not complex when compared to mitosis, the multistage process of DNA duplication and separation observed in eukaryotic cells. However, the frequency of bacterial reproduction is quite extraordinary. For example, under ideal circumstances, the common intestinal bacterium *Escherichia coli* can undergo binary fission and produce a new generation of bacterial cells every 20 minutes (by comparison, producing a new generation of humans takes about 20 years). Within 1 hour, a batch of 100 of these bacteria can become 800 bacteria; in 2 hours, there will be 6,400 bacteria; and in only 3 hours, the original 100 bacteria

■ *Escherichia*
esh-ėr-ē′kē-ä

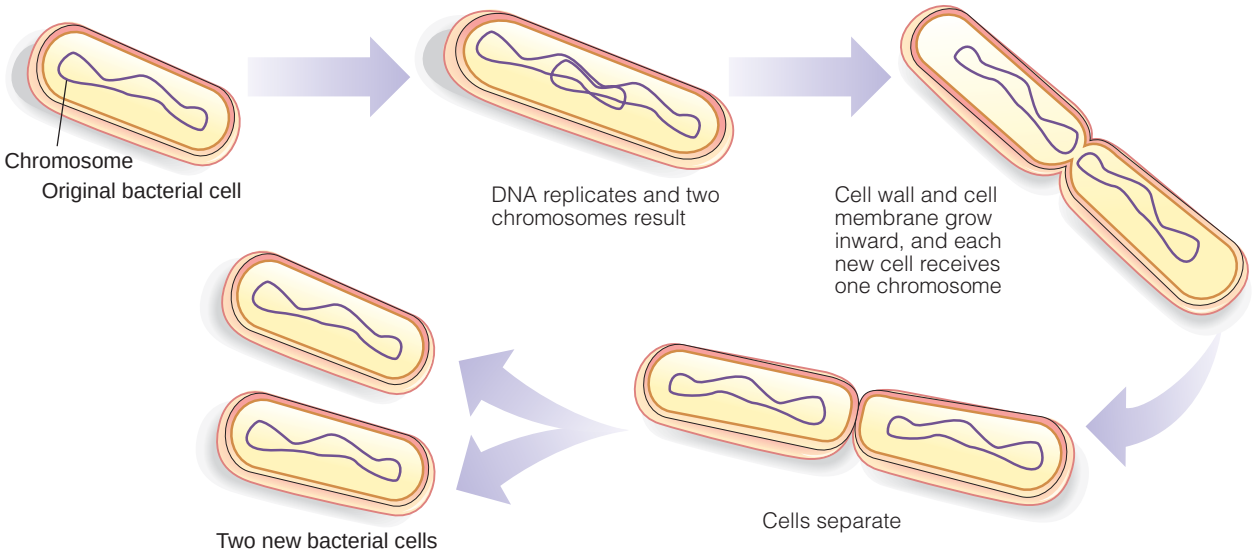


FIGURE 5.8 **Binary Fission in Bacteria.**

will have become 51,200 bacteria. One enterprising mathematician has calculated that a single *E. coli* cell reproducing every 20 minutes could yield in 36 hours enough bacteria to cover the face of the Earth a foot thick!

Then why are we not smothered in bacteria? The answer is that bacteria are susceptible to the same dynamics as any population of plants, animals, or other organisms. Bacteria grow and reproduce wildly for a time, but then the environment catches up to them. Nutrients become scarce, predators become more plentiful, waste products accumulate, water is in short supply, the gaseous environment changes, and from the bacterium's point of view, things get thoroughly out of hand. More bacteria die than reproduce, and the population decreases significantly. We discuss these dynamics and survey some conditions that contribute to microbial reproduction more thoroughly in Chapter 9.

Bacterial Growth

culture medium A mixture of nutrients in which microorganisms can grow.

Bacteria are cultivated in the laboratory on or in materials called culture media (sing., medium). A culture medium is a water solution of various nutrients that encourage the growth of a particular species of microorganism. The medium generally contains a source of energy (for example, glucose), plus sources of carbon, nitrogen, and other essential nutrients. Other substances may be added to encourage the growth of a particular bacterial species. The ability to cultivate bacteria in the laboratory is essential to many applications of microbiology. For example, bacteria must be cultivated to obtain the valuable industrial products they synthesize (Chapter 14).

Culture media may be utilized as liquids or gels. In liquid form, the culture medium is generally called a broth. A typical example is nutrient broth, a "beef soup" that contains beef broth, a derivative of yeast cells called yeast extract, and a protein mixture known as peptone. The gel, or semisolid, form of a culture medium is referred to somewhat imprecisely as an agar. This is because it consists of a broth solidified with agar, a complex carbohydrate derived from algae. Agar is not used as a nutrient by most bacteria; its main claim to fame is that it will remain solid at incubating temperatures as high as 80°C (human body temperature, for comparison, is 37°C). Nutrient agar is a typical example of an agar medium.

Many culture media such as nutrient broth and nutrient agar are general-purpose because they support the growth of many different species of microbes. Microbiologists have also developed a number of special media, called selective media, for cultivating specific types of bacteria. Such a medium will encourage the growth of one species while discouraging the growth of another. Some species of bacteria are known to be fastidious; that is, they require specific nutrients for cultivation in the laboratory. To accommodate these bacteria, microbiologists add special nutrients to nutrient agar to produce a so-called enriched medium. An example is blood agar, which consists of nutrient agar supplemented with sheep red blood cells. This medium encourages the growth of streptococci, which break down the blood cells and cause the normally red medium to become clear, a process called hemolysis (FIGURE 5.9). A physician uses this phenomenon when taking a throat culture to help detect the streptococci of strep throat.

- selective medium A growth medium that contains ingredients to inhibit certain microorganisms while encouraging the growth of others.
- enriched medium A growth medium in which special nutrients must be added to get a species to grow.

FIGURE 5.9 Use of an Enriched Medium.

The extensive research into bacterial culture media has resulted in laboratory protocols for cultivating most human pathogens. Bioterrorists have taken advantage of these advances and have learned to cultivate huge quantities of pathogens in vats capable of holding 10,000 gallons. They add test tube volumes of broth cultures to gallon-sized vessels and incubate the bacteria. When the medium becomes cloudy with growth, they add the contents of the vessel to a larger vessel, one containing 100 gallons of broth. Following incubation, the larger vessel is emptied into a still larger one, and so on, until the bioterrorists have a vat filled with incalculable amounts of bacteria.

But the bacteria-filled broth cannot be used as a bioweapon, and the bioterrorists must dry up the broth and produce a powder. This is accomplished by any of several means. For example, the broth can be sprayed into the heated barrel cylinder of a spray dryer. As the heat evaporates the broth, the dried bacteria fall to the bottom of the cylinder as a powder. Another method involves a heated drum. In this case, the broth is sprayed onto the surface of a heated drum that resembles a steam roller. The broth evaporates quickly and leaves behind a bacteria-rich powder that can be scraped off.

At this point, the process is still not complete. There are too many clumps of bacteria for the powder to be an effective bioweapon. Therefore, the powder must be further processed to a biodust of fine particles that can reach into the lungs or into cracks in the skin. The sophisticated and patented methods required for producing the biodust ensure that bioterrorism can be carried out only by groups that have the technology and expertise to use them.

The Spectrum of Bacteria

It is a common misconception that a great variety of bacteria have been identified and studied. Despite their importance in medicine, research, ecology, and industry, the truth is that the vast majority of bacterial species remain unknown, with no name or available method for cultivation. Indeed, a gram of ordinary garden soil contains thousands of species that will probably remain obscure for many decades to come.

Yet about 4000 species of bacteria, with varying structures, growth patterns, and biochemistry, have been identified. Those who believe that "once you've seen one bacterium, you've seen them all" are well advised to read this section closely—for indeed, the term "bacteria" embodies a bewildering variety of forms.

FIGURE 5.10 The Habitat of Extremophiles. This view of the effluent channel of an alkaline spring in Yellowstone Park shows a mat of cyanobacteria in the foreground. The temperature in the channel is about 75°C (37°C is human body temperature). Archaea live in environments such as these.

Archaebacteria (Archaea)

We open our discussion of bacterial variety by considering a unique type of prokaryote called archaebacteria. These organisms are also known as archaea (sing., archaeon) to distinguish them from the traditional bacteria (in this context, the latter are known as eubacteria, or "true bacteria," as Chapter 2 notes). The reason for the nomenclature shift is the gradually emerging agreement that archaebacteria (archaea) are not bacteria in the traditional sense because their cell walls do not contain peptidoglycan, their cell membranes have unusual lipid compositions, and the RNA in their ribosomes has a unique chemical composition. Largely for these reasons, Carl Woese and his colleagues at the University of Illinois have recommended that these microbes be placed in a domain (or superkingdom) called Archaea.

Another reason for separating archaea from other prokaryotes is the extremely harsh environments in which many species live (FIGURE 5.10). Indeed, a word, "extremophiles," was coined for organisms like these. One group of archaea are the thermoacidophiles. These organisms live under extremely acidic and extremely hot conditions. One archaeon, *Sulfolobus acidocaldarius*, grows well at temperatures of 85°C (about 185°F) and in soil with a pH of 1.0 (the acidity of fuming sulfuric acid). Among the most heat-resistant organisms isolated to date is the archaeon *Pyrolobus fumarii*, which is found in hydrothermal vents at the ocean's bottom. In 1995, scientists found dense communities of these microbes in the boiling waters just above the Macdonald Seamount, an active volcano 150 feet below the surface of the Pacific Ocean near Polynesia. The microbes flourish at temperatures up to 113°C (about 260°F); indeed, they will not grow if the temperature drops below 90°C (194°F) because it gets too cold! Waxy molecules in the cell membrane and many strong linkages between sulfur atoms in the proteins help protect these microbes from the heat that exceeds the heat of boiling water.

- *Sulfolobus acidocaldarius* sul'fō-lō-bus as-i-dō-käl-dār'ē-us
- *Pyrolobus fumarii* pī-rōl'ō-bus fū-mär'ē-ē

Another group of archaea are the methanogens. These prokaryotes live solely on carbon dioxide, nitrogen, and water. They produce methane under oxygen-free conditions and thrive in volcanic rock, marshes, lake bottoms, and animal feces (interestingly, they were in animal intestines all along, but remained unidentified until fairly recently).

A third group of archaea are the extreme halophiles. These organisms live in high-salt environments, such as Utah's Great Salt Lake. Some species have red pigments in their cytoplasm; such cellular pigments account for the redness in salt collection ponds near California's San Francisco Bay.

Archaea were so named because microbiologists believe the organisms existed under primitive Earth conditions. At one time, scientists even thought that archaea predated traditional bacteria, which evolved from them. However, that notion was challenged in recent years by comparative analyses of the DNA in prokaryotes. The current thinking is that an as-yet-unidentified ancestral microbe gave rise to both archaea and traditional bacteria. It is conceivable that traces of the ancestral microbe are waiting to be discovered somewhere in a primordial swamp.

- archaebacterium The former term for a unicellular organism in the domain *Archaea*.
- thermoacidophile An archaeal organism living under high temperature and high acid conditions.
- extremophile A microorganism that lives in extreme environments, such as high temperature, high acidity, or high salt.
- methanogen An archaeal organism that lives on simple compounds in anaerobic environments and produces methane during its metabolism.
- extreme halophile An archaeal organism that grows at very high salt concentrations.

Photosynthetic Bacteria

Among the traditional bacteria (i.e., eubacteria) are the cyanobacteria and other photosynthetic bacteria that have chlorophyll pigments dispersed in their cytoplasm. These bacteria have different colors due to varying forms of the pigments; and because they use sulfur extensively in their chemical reactions, many are grouped as green

sulfur bacteria, purple sulfur bacteria, and purple nonsulfur bacteria. These microbes use photosynthesis to produce energy-rich organic matter that other species of bacteria can absorb and use in their metabolism when the photosynthetic microbes die. The photosynthesizers are known as autotrophic microbes because they synthesize their own food (*auto-* refers to "self," and *troph* refers to "feeder"; hence, "self-feeder"). By comparison, microbes that use preformed organic matter for food are known as heterotrophic microbes (*hetero-* refers to "other," meaning from other sources). By providing organic matter at the base of the food chain, the photosynthesizers occupy a key position in the nutritional patterns of nature.

■ heterotrophic microbe A microbe that requires preformed organic matter for its energy and carbon needs.

The cyanobacteria have green chlorophyll pigments. When they contaminate aquaria and swimming pools, cyanobacteria cause the water to become an eerie blue-green color with a slimy feel. They also thrive in freshwater ponds, where they form deposits identical to those of cyanobacteria living on Earth over 3 billion years ago. Those massive limestone (calcium carbonate) deposits were abundant in virtually all freshwater and marine environments until about 1.6 billion years ago. Known as stromatolites, such deposits are still being formed, but only where the environment provides much light, acid, and salt. Examples of these environments occur in Western Australia.

In addition to photosynthesis, some species of cyanobacteria carry out nitrogen fixation. In this process, the cyanobacteria take up nitrogen from the atmosphere and use it to synthesize ammonia and other nitrogen-containing substances, which plants can incorporate into organic compounds when the bacteria die. The process occurs within specialized cyanobacterial cells called heterocysts. These cells produce the key enzyme for trapping nitrogen. The nitrogen-containing compounds are also shared with photosynthetic cells of the cyanobacterial colony, which, in turn, produce carbohydrates to supply the energy needs of the heterocysts. Such a mutually beneficial relationship is called symbiosis. Because they carry out photosynthesis as well as nitrogen fixation, cyanobacteria are among the most independent organisms on Earth. Moreover, they were probably the first organisms to introduce atoms of oxygen into the planet's atmosphere.

■ nitrogen fixation The chemical process by which microorganisms convert nitrogen gas (N_2) into ammonia.

■ symbiosis An interrelationship between two populations of organisms where there is a close and permanent association.

Heterotrophic Eubacteria

Most species of what we commonly refer to as "bacteria" are the heterotrophic eubacteria. The majority of these bacterial species are key players in the global cycling of nitrogen, sulfur, iron, phosphorus, and other nutrients. Most species are decomposers (organisms that break down chemical compounds in the environment), but many are producers (organisms that synthesize compounds for their own use and for other organisms). For example, heterotrophic bacteria belonging to the genera *Azotobacter* and *Rhizobium* are among the few organisms (other than cyanobacteria) that trap nitrogen from the atmosphere and synthesize useful organic compounds. We discuss these microbes at length in Chapter 16.

■ *Azotobacter*
ä-zo'to-bak-tėr

■ *Rhizobium*
rī-zō'bē-um

■ *Lactobacillus*
lak-tō-bä-sil'lus

Among other important heterotrophic eubacteria are *Escherichia coli* and *Lactobacillus* species. Strains of *E. coli,* shown in FIGURE 5.11, live in the human intestine and help newborns digest milk by breaking down its lactose. This microbe is also a highly effective research tool in physiology, biochemistry, and genetics (probably more is known about *E. coli* than any other organism on Earth), and it produces many industrial enzymes, vitamins, and amino acids. *Lactobacillus* species live in the female genital tract and help guard against infection by other microbes. They are also used in the large-scale manufacturing of cheese, sour cream, yogurt, and other fermented milk products, as we note in Chapter 14.

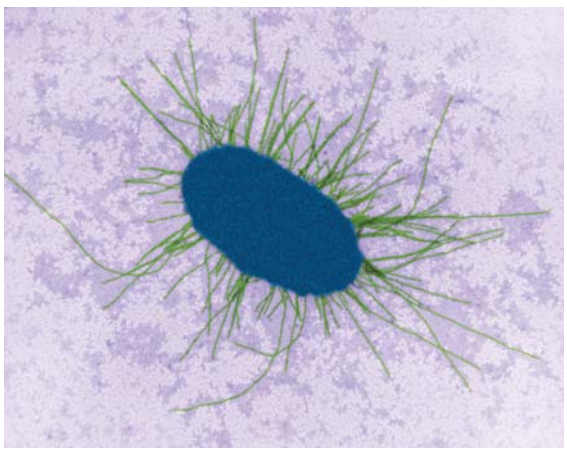


FIGURE 5.11 **The Heterotrophic Bacterium *Escherichia coli*.** In this transmission electron micrograph, *E. coli* displays short, hairlike pili on its surface. The pili encourage the bacteria to adhere to the host's intestinal tissues (×40,000).

Pseudomonas
sū-dō-mō′näs

The heterotrophic bacteria include many other species with medical, industrial, and environmental importance. Among the more interesting are members of the genus *Pseudomonas*. One species, *P. aeruginosa,* produces a soluble blue-green pigment that emits a green glow when it infects burnt tissue and wounds. In the soil, other species of the genus produce a large variety of enzymes that contribute to the breakdown of pesticides and similar waste chemicals. Unfortunately, some species also detract from the quality of soil by breaking down nitrates and converting these valuable plant nutrients to nitrogen gas, which is then released to the atmosphere.

Serratia marcescens
ser-rā′tē-ä mär-ses′sens

Heterotrophic bacteria include many pathogens responsible for human disease, as well as several other microbes. Included here is *Serratia marcescens*, a gram-negative bacterium distinguished by the blood-red pigment it produces when it forms colonies. Although *S. marcescens* can infect the respiratory tract in patients with compromised immune systems, the organism is better known for its influence on the course of history. In 332 BCE, Alexander the Great and his army of Macedonians were laying siege to the city of Tyre in what is now Lebanon. The siege was not going well. Then one morning, blood-red spots appeared on several pieces of bread (actually they were colonies of *S. marcescens*). At first, the "blood" was thought to be an evil omen, but a soothsayer named Aristander pointed out that the red material was coming from inside the bread. This suggested that blood would be spilled within Tyre and that the city would fall. Alexander's troops were buoyed by this interpretation; with renewed confidence, they charged headlong into battle and captured the city. The victory opened the Middle East to Alexander and the Macedonians. Their march did not stop until they reached India.

Because of the bright red pigment of its colonies, *S. marcescens* was also used in the past to test wind currents that might carry bioweapons. Balloons filled with broth cultures of the bacteria were burst at a given point, and open plates of nutrient agar were set out for a specific time period at numerous other points. If bright red colonies appeared on any of the plates after incubation, that was evidence that bacteria released by a bioterrorist could travel from the starting point to that point. Since somewhat pathogenic strains of *S. marcescens* are now known to exist, tests such as these are no longer performed.

Spiral and Filamentous Bacteria

The spiral bacteria resemble springs that have been partially stretched out. They can be either spirochetes or spirilla. Spirilla have flexible cells and flagella at the ends of the spiral, and spirochetes have rigid cells and long flagella inserted beneath the outer membrane of the cell wall. These flagella rotate and allow the spirochetes to move rapidly. One species of spirochete causes syphilis; another causes Lyme disease (Chapter 19).

actinomycete A soil bacterium that exhibits funguslike properties when cultivated in the laboratory.

Many bacteria occur as long, chainlike branching forms known as actinomycetes (*actino-* means "radiating"; *mycetes* refers to "fungus," because the branching chains of cells are funguslike). Within this group are species of *Streptomyces,* which produce numerous antibiotics including tetracycline, erythromycin, and neomycin. Actinomycetes form very resistant spores at the tips of their filaments, a feature that allows them to remain alive in difficult environments such as soil (to which they give a characteristic mustiness). It should be noted that although actinomycetes form chains of cells, each operates independently.

Gliding and Sheathed Bacteria

Beggiatoa
bej′jē-ä-tō-ä

Thiothrix
thī′ō-thriks

Certain species of bacteria produce a slimy substance, then move by gliding along in it. Wavelike contractions of the outer cell membrane propel these bacterial "gliders" through the slime. Two important genera of gliding bacteria, *Beggiatoa* and *Thiothrix*, live in sulfur-rich muds and break down foul-smelling hydrogen sulfide, releasing sulfur that can then be used by other organisms.

Another group of gliding bacteria, the myxobacteria, have a unique developmental cycle involving the formation of reproductive structures called fruiting bodies. When nutrients are exhausted, the bacteria congregate and interact with one another, eventually producing a stalk with a mass of cells at the top. The cells differentiate into sporelike bodies that are highly resistant to environmental stresses and thus permit the myxobacteria to survive until conditions improve.

- myxobacteria A group of soil-dwelling bacteria that exhibit multicellular behaviors.

Sheathed bacteria are a type of filamentous (chainlike) bacteria having cell walls enclosed in a sheath of complex carbohydrates and proteins. The sheath helps protect the bacteria from predators and environmental stresses, and it permits the bacteria to attach to food particles. Members of the genus *Spherotilus* are in this group.

Predatory and Other Bacteria

Among the more intriguing of bacterial forms are the bdellovibrios, a group of rod-shaped bacteria that prey on other bacteria. A bdellovibrio bacterium attaches to the surface of a host bacterium, then rotates and bores a hole through the cell wall. It takes control of the host cell and grows in the space between the cell wall and cell membrane, killing the host bacterium in the process. *Bdellovibrio bacteriovorus* is the most thoroughly studied species of the group.

- *bacteroides* bak-tė-roi′dēz
- bacteroides Gram-negative, anaerobic, rod-shaped bacteria that are unusual because their plasma membranes contain sphingolipids.

The bacteroides are a group of gram-negative bacterial rods that live in oxygen-free environments. Several species live in the stomach of the cow and digest the cellulose in plant cells, a chemical process accomplished by few other organisms (we explore the implications of this process more completely in Chapter 15). Human feces contain large amounts of bacteroides, which are probably very helpful in our digestive processes. Indeed, an estimated 30% of the bacterial mass isolated from human feces consists of bacteroides.

- chemolithotrophic bacteria A group of bacteria that derive their energy from chemical reactions and use simple carbon compounds and inorganic materials to synthesize larger molecules.
- *Nitrosomonas* nī-trō-sō-mō′näs
- *Nitrobacter* ni-trō-bak′tėr

Chemolithotrophic bacteria are a group of bacteria that derive their energy from chemical reactions and use simple carbon compounds and inorganic materials to synthesize larger molecules. For example, chemolithotrophic bacteria such as *Nitrosomonas* and *Nitrobacter* species use carbon dioxide for their carbon needs and grow in environments containing nitrate or nitrite ions. This type of biochemistry is an essential feature of the cycles of nature.

The acid-fast bacteria include members of the genus *Mycobacterium,* the so-called mycobacteria. These rod-shaped bacteria have large amounts of mycolic acid in their cell walls, a factor that makes them very difficult to stain. However, when heat or other agents are used to force stain into the cytoplasm, the bacteria resist decolorization even though a dilute acid-alcohol solution is used. Therefore, they are said to be acid-fast (or acid-resistant). Many mycobacteria are free-living, but there are two notable pathogens in the group: *M. tuberculosis,* the cause of tuberculosis; and *M. leprae,* which causes leprosy. The acid-fast characteristic is a key factor in their detection.

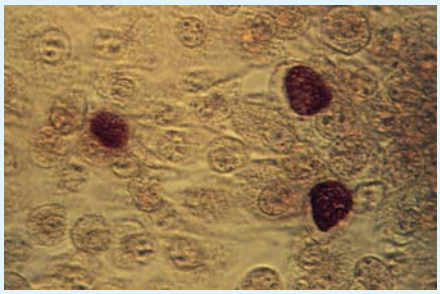
Submicroscopic Bacteria

Among the very small bacteria are the rickettsiae, chlamydiae, and mycoplasmas. These forms are said to be submicroscopic because they cannot be seen clearly with a light microscope; an electron microscope is required to see them in detail.

- rickettsia (pl. rickettsiae) A very small bacterial cell generally transmitted by arthropods; most rickettsiae are cultivated only within living tissues.
- chlamydia (pl. chlamydiae) A very small, round, pathogenic bacterium visible only with the electron microscope and cultivated within living cells.
- mycoplasma One of a group of tiny submicroscopic bacteria that lacks cell walls and is visible only with an electron microscope.

Rickettsiae were discovered by and named for Howard Taylor Ricketts, a bacteriologist from the University of Chicago. In 1910, Ricketts was investigating the cause of Rocky Mountain spotted fever, a blood disease accompanied by a skin rash and high fever. Ricketts identified ticks as the mode of transmission for the disease, but in the course of his work he was stricken with a closely related disease and died. Rickettsiae are about 0.45 µm in diameter and are extremely difficult to cultivate in the laboratory; they are transmitted among their hosts almost exclusively by arthropods (such as fleas, ticks, and lice). During the 1990s, a tickborne rickettsial disease called ehrlichiosis occurred sporadically in the northeastern United States.

1. An educated, professional woman met a gentleman at a friend's house one evening. She was director of a New York law firm. The man was equally successful in his professional career.
2. The couple hit it off immediately. There were many evenings of quiet candlelit dinners, and soon, they became sexually intimate. Neither one used condoms or other means of protection.
3. Three days after having intercourse, the woman began experiencing fever, vomiting, and severe abdominal pains. She immediately made an appointment to see her doctor.



4. Assuming the illness was an intestinal upset, the physician prescribed appropriate medication. The woman was actually suffering from chlamydia, but the fact that she was sexually active did not come up during the examination.
5. Feeling better, the woman continued her normal routine. But 6 months later, with no apparent warning, she collapsed on a New York City sidewalk.
6. The woman was rushed to a local hospital, where doctors diagnosed a chlamydial infection by observing the dark inclusion bodies typical of chlamydia (see figure). They performed emergency surgery: her uterus and Fallopian tubes were badly scarred. She recovered, but the scarring left her unable to have children.

FIGURE 5.12 **A Case of Chlamydia.** This case occurred in a 32-year-old professional woman. Tragic complications of the disease resulted because she and her doctor neglected to consider that she could be suffering from a sexually transmitted disease.

At 0.25 µm, chlamydiae are a step below rickettsiae in size. One species of chlamydiae called *Chlamydia trachomatis* causes a common sexually transmitted disease known as chlamydia (note that the disease and the organism have the same name). Chlamydia, the disease, is accompanied by burning pain in the reproductive tract and possible complications in the pelvic organs; it is estimated to affect over 4 million Americans annually. One case is presented in FIGURE 5.12.

Mycoplasmas are the only bacteria that lack a cell wall. A single membranous layer of lipids encloses these tiny cells, which measure about 0.15 µm in diameter and are the smallest known bacteria. Mycoplasmas appear under the electron microscope as irregular blobs, and certain species cause mild pneumonia in humans.

Bacterial Pathogens

Bacteria are probably best known to the public as agents of human disease. The notion that bacteria are involved in infectious disease, the germ theory of disease, was developed by Louis Pasteur during the latter part of the 1800s, as Chapter 1 explores. Verification of the germ theory was offered by Robert Koch, a German physician and a contemporary of Pasteur. Following the lead of Koch and Pasteur, microbiologists from around the world participated in the Golden Age of Microbiology, a 60-year period lasting from about 1860 to 1920, during which a majority of the bacterial pathogens of infectious disease were identified.

Bacteria can cause disease in a number of ways. In some cases, bacteria grow and multiply in extraordinary numbers in body tissues and cause cellular death—the bacteria that cause tuberculosis work in this way. At other times, bacteria produce substances to help them overcome body defenses—staphylococci, for example, produce an enzyme that clots blood and forms a protective layer of clotting material around the invading bacteria; this layer negates the body's attempt to attack the bacteria and destroy them.

In other instances, bacteria synthesize poisonous substances called toxins. Toxins interfere with the chemical activities of cells and tissues. For example, the bacterium

that causes tetanus produces a powerful toxin that interferes with the relaxation of muscles after they contract. The muscles undergo severe spasms and "lock" into place ("lockjaw" is one effect). Another toxin producer is *Clostridium botulinum*, the organism that causes botulism. The toxin produced by *C. botulinum* has been developed as a weapon of bioterrorism because it can be added to water and, when ingested, causes nerve paralysis that is highly lethal.

Bacterial disease can also result from an excessive immune response in the body, a response that leads to inflammation and local tissue damage. In the case of endocarditis, for instance, streptococci elicit antibodies from the immune system, and the antibodies unite with bacteria at the heart valves; progressive deterioration of the valves results in heart failure.

The human body responds to disease by defending itself with chemical substances such as interferon (an antiviral substance) and lysozyme (an antibacterial substance that destroys the cell wall). White blood cells attempt to engulf and destroy bacteria through the process of phagocytosis. In addition, the body calls the immune system into action. The production of activated T cells and antibodies is stimulated by chemicals associated with bacteria and other microbes. Ultimately the T cells and antibodies attack the bacteria and destroy them, as we describe in depth in Chapter 17. We also look more closely at specific bacterial diseases in Chapter 19.

Despite these negative images, it is important to remember that of the thousands and thousands of bacterial species, a tiny percentage (less than 1%) are pathogenic. The vast majority of bacterial species are beneficial to humans: They participate in numerous industrial processes, synthesize many vital chemicals, and work their magic in recycling processes taking place in the soils and waters of the Earth. Although bacteria and other microbes have largely earned their reputations from the diseases they cause, they have numerous positive characteristics and functions. We shall see many of those in other chapters.

A Final Thought

When you pick up this book for the first time, you may experience a moment anticipating your first look at bacteria. Perhaps you leaf through the pages, turn back to see a photograph a second time, then pause and think: "Is that all there is? Little rods and circles?"

Our first encounter with bacteria is often a disappointing (and perhaps exasperating) experience. Since early childhood, we have been taught to loathe and despise bacteria, and we have been schooled in all the dastardly deeds they do. "Wash your hands" we are admonished; "Don't eat it if it falls on the ground." And on and on. We expect bacteria to be grotesque and fearsome monsters. We expect them to rank with death and taxes. But they turn out to be little sticks and rods, not very dangerous-looking at all. So what's the big deal?

Perhaps that's good. Perhaps we need to wipe away any preconceived notions of bacteria and start rebuilding our views—a process that will take us through the complexity of bacterial structures, give us insight into their chemistry, point up their remarkable genetics, and stress their importance in food production, industrial manufacturing, and soil ecology.

It's going to take some time to absorb the importance of bacteria to our lives, but for now try to understand that bacteria are more than the tiny rods you see on these pages or under the microscope. The electron microscope has yielded a wealth of information about their structure (as this chapter demonstrates) and studying bacterial structure gives us a clue to what they do. This "what they do" part explains their importance to us. Please stay tuned.

Questions to Consider

1. Suppose a bacterium had the opportunity to form a glycocalyx, a flagellum, a pilus, or a spore. Which do you think it might choose? Why?
2. Extremophiles are of interest to industrial corporations, which see these bacteria as important sources of enzymes that function at temperatures of 100°C and in extremely acidic or basic conditions (the enzymes have been dubbed "extremozymes"). What practical uses can you foresee for these enzymes?
3. In the fall of 1993, public health officials found that the water in a Midwestern town was contaminated with sewage bacteria. The officials suggested that homeowners boil their water for a couple of minutes before drinking it. Would this treatment remove all traces of bacteria from the water? Why?
4. Researchers have estimated that, in broad terms, about one-third of human feces is composed of bacteria. That being the case, about how much bacteria do we "produce" in a week? In a year? How can this be possible?
5. Suppose this chapter on the structure and growth of bacteria had been written in 1940, before the electron microscope became available. Which parts of the chapter would probably be missing?
6. "Bacteria are all the same. Once you've seen one, you've seen 'em all!" What evidence could you present to counter this statement?
7. There are thousands of species of bacteria, yet with few exceptions, all of them are variations of three shapes: the rod, the sphere, and the spiral. Do you find this strange? Why or why not?

Key Terms

Informative facts are necessary for the expression of every concept, and the information for a concept is founded in a set of key terms. The following terms form the basis for the concepts of this chapter. On completing the chapter, you should be able to explain or define each one:

acid-fast bacteria
actinomycetes
archaebacteria
autotrophic microbes
bacilli
bacteroides
bdellovibrios
binary fission
cell wall
chemolithotrophic bacteria
chlamydiae
cocci
culture medium
cyanobacteria
differential technique
enriched medium
eukaryotes
extreme halophiles
extremophiles
flagellum
fluid mosaic
glycocalyx
Gram stain technique
heterotrophic microbes
methanogens
mycoplasmas
myxobacteria
nitrogen fixation
nucleoid
nutrient agar
nutrient broth
peptidoglycan
periplasm
pilus
prokaryote
rickettsiae

selective medium
Serratia marcescens
simple stain technique
spirilla
spirochete
spore
staphylococcus
symbiosis
thermoacidophiles

http://microbiology.jbpub.com/microbes/3e

To explore these topics in more detail, visit this book's Student Companion Web Site at **http://microbiology.jbpub.com/microbes/3e**. The site features chapter outlines, study quizzes, an interactive glossary, animated flashcards, crossword puzzles, and links to news, research, and reference sites on the Web.