2.1 The Prokaryotes: Eubacteria and Archaea

Organisms in Domain Eubacteria (commonly called bacteria) and Domain Archaea are prokaryotes. They are single-celled organisms, and they lack membrane-bound organelles. Prokaryotes are the smallest organisms on Earth (**Figure 1**) and some of the most important. Most prokaryote species are only 1 μm to 2 μm long—500 to 1000 of them would fit side by side across the dot of this letter "i."

LEARNING TIP

Micrometres (μm)
A micrometre, also known as a micron, is indicated by the symbol μm. It is a unit of length equal to one millionth of a metre.

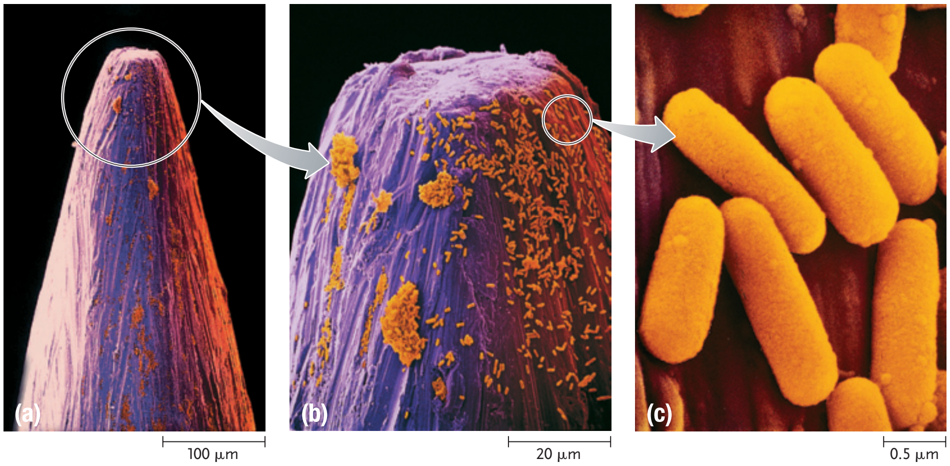

Figure 1 *Bacillus* bacteria on the point of a pin. The images are magnified (a) 70×, (b) 350×, and (c) 14 000×.

Figure 2 Many prokaryotes inhabit extreme environments. Some species live in the high temperatures found in boiling hot springs.

Despite their small size, prokaryotes are dominant forms of life that live in every imaginable habitat. They live inside and on the surface of other organisms, in water and soil, deep within Earth, in boiling hot springs (**Figure 2**), and even in ice. For example, more than 100 trillion bacteria live on and within your body. These bacteria outnumber all the other cells in your body! In fact, prokaryotes vastly outnumber all living things on Earth. Their total mass exceeds that of animals and possibly all plant life on Earth.

Everything we know so far about prokaryotes is based on a tiny fraction of the total number of species. Only about 10 000 prokaryote species have been isolated and identified, and this may represent as little as 1 % of the total number of species. Why have we identified so few species, and why are we not even sure how many prokaryotes there might be? In order to identify and study prokaryotes, scientists must first find and collect live specimens, then grow them in the laboratory. Unfortunately this is extremely difficult, partly because many prokaryotes live in remote locations and in extreme conditions.

Why Prokaryotes Are Important

Prokaryotes are extremely important organisms in many ways. Bacteria are the prokaryotic organisms most familiar to us. They are perhaps best known for their harmful effects. Bacteria are responsible for many diseases in humans and in other organisms. Infectious bacteria are called **pathogens** and are responsible for many human deaths each year. Bacterial diseases include cholera, leprosy, typhoid fever, strep throat, salmonella poisoning, and tuberculosis. Bacteria also infect livestock and crops and therefore threaten our primary food sources.

pathogen a disease-causing agent, often a virus or micro-organism

UNIT TASK BOOKMARK

Is your chosen group of species threatened by pathogens? Are any other factors, such as climate change, contributing to the threat?

It is important to keep in mind that from the perspective of the infected organism, pathogens are harmful. However, diseases that harm one species can benefit another. For example, diseases that weaken predators benefit their prey.

Although some bacteria can be harmful, others play a very positive overall role on Earth, and without them we could not survive. Bacteria, and some archaea, play key roles in ecosystems. Many are decomposers, and others are producers. These micro-organisms also recycle nutrients and are vital to biogeochemical cycles. Bacteria fix, or convert, atmospheric nitrogen into chemical compounds that can be used by plants. Photosynthetic bacteria are the major producers in marine ecosystems and are therefore major producers of atmospheric oxygen.

Bacteria are also important residents in the intestines of animals. For example, humans rely on bacteria in the large intestine to produce needed vitamins K and B12. So, although the bacteria benefit from living within the intestine, the individual also benefits from the action of the bacteria. This type of relationship between two species that are interdependent, where each benefits from the other, is known as **mutualism**.

Bacteria also have many commercial uses. They are essential in the production of foods such as cheeses, yogurt, soy sauce, and chocolate (**Figure 3**)! Bacteria also produce substances known as **antibiotics,** which can destroy or inhibit the growth of other micro-organisms. Genetic engineers have even modified some bacteria to produce medically valuable compounds, including insulin and human growth hormone.

Archaea are a group of prokaryotes that were discovered only about 40 years ago. Scientists do not know as much about archaea as they do about bacteria, but we do know that these species play key roles in many ecosystems. Archaea live in some of the most extreme environments on Earth, such as hot springs, Arctic ice floes, and highly acidic waters. They also live in the intestines of some animals, including humans. No species from Domain Archaea are known to cause disease.

Figure 3 Yeast and bacteria are used in the process that produces chocolate from cacao (*Theobroma cacao*) beans.

mutualism a relationship between two species that live in very close association with each other, whereby each benefits from the association

antibiotic a substance that can kill or weaken micro-organisms; natural antibiotics are produced by bacteria or fungi, whereas synthetic antibiotics are manufactured

CAREER **LINK**

Cheese Maker
To learn more about careers in the cheese-making industry,

GO TO NELSON SCIENCE

The Domain Eubacteria

Fossil evidence shows that prokaryotes have lived on Earth for more than 3.5 billion years. Although fossils cannot provide information about how Eubacteria evolved, genetic studies suggest that species in this domain diversified early.

Classification and Phylogeny

The Domain Eubacteria has more than 12 separate evolutionary branches, or groups. **Figure 4** shows six particularly important groups of bacteria.

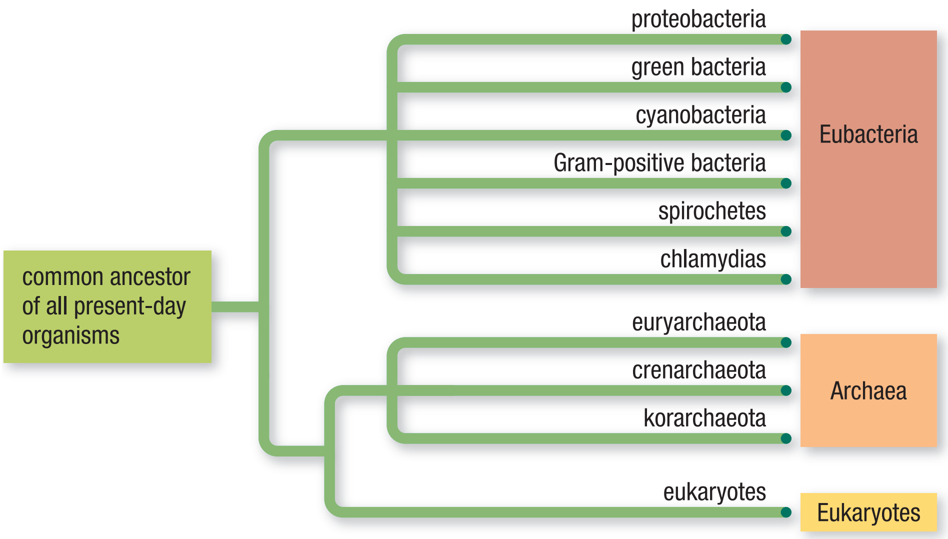

Figure 4 This phylogenetic tree shows the relationships among the three domains of life: Eubacteria, Archaea, and Eukaryotes. For simplicity, only the six major groups of bacteria are shown here.

These six groups of bacteria are extremely diverse. They vary dramatically in how they obtain energy and nutrients, in their ecological roles, and in their importance to humans.

Table 1 lists the key features of each group of bacteria. Three of these major groups are photosynthetic. Proteobacteria and green bacteria, however, use a process that is very different from photosynthesis in plants. They do not use water or release oxygen, and they use different forms of chlorophyll.

Table 1 Key Features of the Six Major Groups of Bacteria

Group	Key features
proteobacteria (purple bacteria)	• Some are photosynthetic but use a form of photosynthesis that differs from that of plants. • Ancient forms of these bacteria were the likely ancestors of eukaryotic mitochondria. • Some are nitrogen fixing. • They are responsible for many diseases, including bubonic plague, gonorrhea, dysentery, and some ulcers.
green bacteria	• They use a form of photosynthesis that differs from that of plants. • They are usually found in salt-water environments or hot springs.
cyanobacteria (blue-green algae)	• They use a form of photosynthesis similar to plants and other eukaryotes. • Ancient forms of these bacteria were the likely ancestors of eukaryotic chloroplasts. • They play major roles as producers and nitrogen fixers in aquatic ecosystems. • They form symbiotic relationships with fungi.
Gram-positive bacteria	• They cause many diseases, including anthrax, strep throat, bacterial pneumonia, and meningitis. • They are used in food production (for example, lactobacillus is used in yogurt and probiotic products). • Some have lost their cell wall. • One type—mycoplasmas—are the smallest known cells (0.1 μm to 0.2 μm).
spirochetes	• Their spiral-shaped flagellum is embedded in their cytoplasm. • They move with a corkscrew motion. • They cause syphilis. • Symbiotic spirochetes in termite intestines digest wood fibre.
chlamydias	• All are parasites that live within other cells. • They cause chlamydia, one of the most common sexually transmitted infections. • They cause trachoma, the leading cause of blindness in humans.

Characteristics

Images of bacteria taken with a standard electron microscope typically show little more than a cell wall and a plasma membrane surrounding cytoplasm (**Figure 5**). However, these prokaryotic cells are relatively complex. A bacterium's chromosome is a single loop of DNA (deoxyribonucleic acid) that is found in a region called the nucleoid. Ribosomes, which are used in protein synthesis, are scattered throughout the cytoplasm. Bacteria often have one or more flagella for movement and small hair-like structures called pili (singular: pilus). The pili are made of stiff proteins and help the cell attach to other cells or surfaces. **Figure 6** shows the structure of a typical bacteria cell.

Figure 5 Bacterial cells do not have membrane-bound organelles.

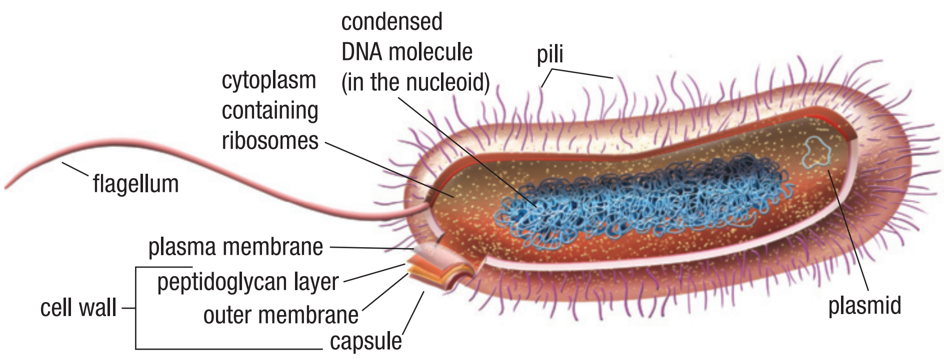

Figure 6 A representative bacterial cell

In addition to a single chromosome, many bacteria have one or more plasmids in their cytoplasm. A **plasmid** is a small loop of DNA that usually carries a small number of genes. The genes are not essential for cellular functions but often provide some advantage to the cell. For example, genes that give bacteria resistance to antibiotics are often found on plasmids.

plasmid a small loop of DNA often found in prokaryotic cells; usually contains a small number of genes

Bacteria have complex cell walls composed primarily of peptidoglycan, a large molecule that forms long chains. These chains become cross-linked, making the cell wall strong and rigid. Some bacteria are also surrounded by a sticky **capsule**. The capsule reduces water loss, resists high temperatures, and helps keep out antibiotics and viruses.

capsule an outer layer on some bacteria; provides some protection for the cell

coccus a round bacterial cell

bacillus a rod-shaped bacterial cell

spirillum a spiral or corkscrew-shaped bacterial cell

Bacteria cells vary considerably in shape. Three common shapes are **coccus** (plural: cocci), or round; **bacillus** (plural: bacilli), or rod shaped; and **spirillum** (plural: spirilli), or spiral (**Figure 7(a)** to **(c)**). Bacteria cells often occur in particular arrangements, such as pairs, clumps, or strings. The prefixes *diplo-*, *staphylo-*, and *strepto-* are used to describe these arrangements (**Figure 7(d)**). Many species names are based on these easily recognizable characteristics. For example, the species of bacteria responsible for strep throat is *Streptococcus pyogenes*.

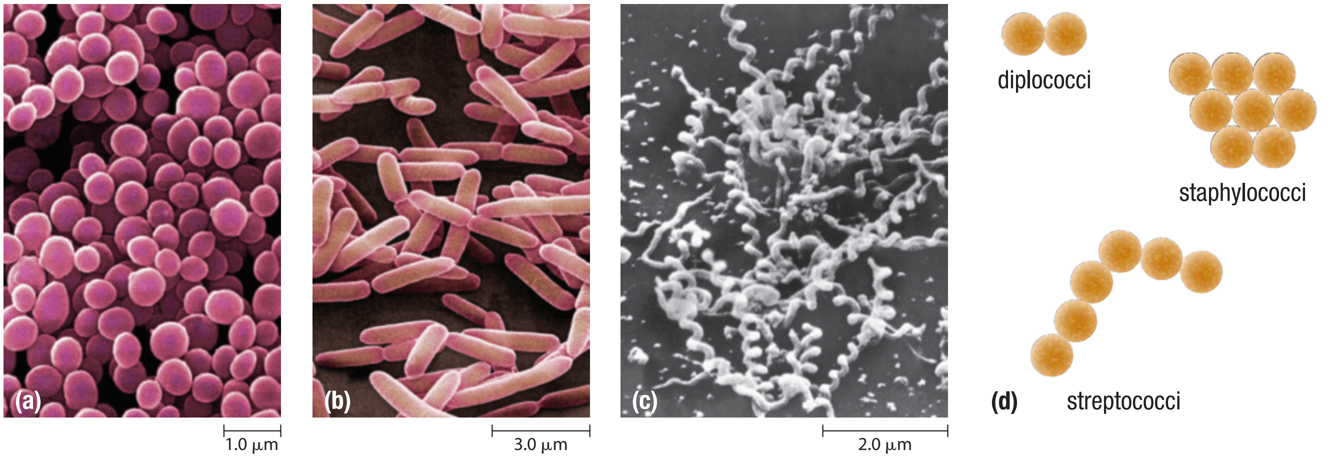

Figure 7 Bacteria cells have three common shapes: (a) cocci, (b) bacilli, and (c) spirilla. (d) They often occur in pairs (diplo), clumps (staphylo), or strings (strepto).

METABOLISM

Bacteria are extremely diverse in the ways they get nutrients and energy from their surroundings. Autotrophic bacteria make their own food. They assemble complex carbon molecules from simple **inorganic chemicals**—substances such as carbon dioxide, water, and minerals that are part of the abiotic environment. Heterotrophic bacteria get their nutrients from carbon containing **organic chemicals** found in other living organisms or their remains.

inorganic chemical a chemical that has an abiotic origin; some simple substances that are produced by organisms are also classified as inorganic

organic chemical in biology, any chemical that contains carbon and is produced by living things; carbon dioxide is an exception—it is produced during respiration but is classified as inorganic

The two primary sources of energy for living things are sunlight and chemical energy. We are most familiar with the chemical energy contained in organic chemicals such as sugars, fats, and proteins. Many bacteria can also get energy from inorganic chemicals such as hydrogen, sulfur, and iron compounds.

All animals and plants are **obligate aerobes**: they need oxygen, obtained through the process of respiration, in order to get energy from food. Some bacteria are obligate aerobes, and others are **facultative aerobes**. These bacteria perform aerobic respiration in the presence of oxygen and anaerobic respiration, or anaerobic **fermentation**, when oxygen is absent. Still other bacteria are **obligate anaerobes**: they cannot live in environments where oxygen is present.

obligate aerobe an organism that cannot survive without oxygen

facultative aerobe an organism that can live with or without oxygen

fermentation an anaerobic process that releases chemical energy from food

obligate anaerobe an organism that cannot survive in the presence of oxygen

REPRODUCTION

Prokaryotes normally reproduce asexually. In this process, a parent cell divides by **binary fission**, producing two daughter cells. Each daughter cell receives an exact copy of the genetic material from the parent cell—its chromosome and plasmids. Sometimes mistakes are made when the genetic material is copied.

binary fission the division of one parent cell into two genetically identical daughter cells; a form of asexual reproduction

Copying errors result in mutations, or changes in the genetic makeup of the cell. Bacteria reproduce very quickly, so they mutate more often than organisms that reproduce more slowly. A bacterial gene mutates roughly 1000 times as often as a eukaryotic gene. These mutations increase the genetic diversity in populations of bacteria (**Figure 8(a)**).

Bacteria also increase their genetic diversity by gaining new DNA. This may happen when a bacterium is infected by a virus or through conjugation and transformation. In **conjugation**, one bacterial cell passes a copy of a plasmid to a nearby cell through a hollow pilus (**Figure 8(b)**). This can benefit the recipient cell if the plasmid provides beneficial genes. Conjugation is considered a form of sexual reproduction, because two different cells are sharing genetic information. **Transformation** occurs when a cell picks up a loose fragment of DNA from its surroundings and uses it. These DNA fragments may have been released into the environment when other cells died. If the new DNA came from a different species, the process is called **horizontal gene transfer**.

conjugation a form of sexual reproduction in which two cells join to exchange genetic information

transformation a process in which a bacterial cell takes in and uses pieces of DNA from its environment

horizontal gene transfer the transfer of genetic information from one species into a different species

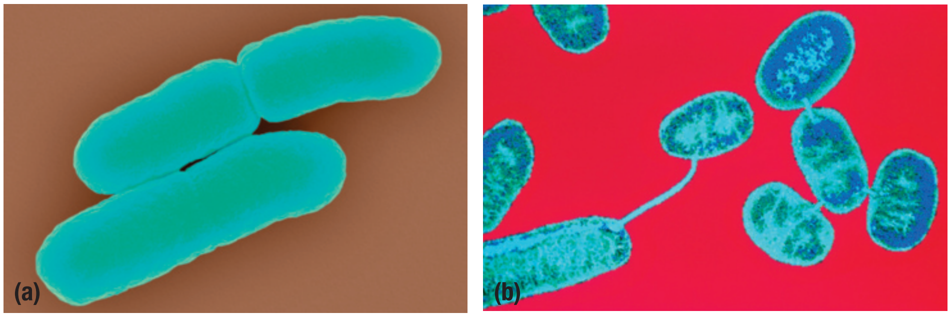

Figure 8 (a) The *E. coli* (*Escherichia coli*) cell on the top is dividing by binary fission. (b) Pairs of bacteria are joined by a pilus and are undergoing conjugation. One cell is transferring a copy of a plasmid to another cell.

endospore a dormant structure that forms inside certain bacteria in response to stress; protects the cell's chromosome from damage

As you observed in the mini investigation at the beginning of this chapter, organisms that can double their population size in only 1 h can produce millions of individuals in a matter of hours. This fast reproduction can have dramatic ecological consequences, such as "algal blooms" in aquatic ecosystems (**Figure 9**). Algal blooms can reduce the oxygen content of water bodies and threaten other organisms, including fish.

Some bacteria have a unique strategy for surviving unfavourable conditions: they produce endospores. An **endospore** is a highly resistant structure that forms around the chromosome when the cell is under stress. Endospores can withstand extreme conditions and remain dormant until conditions improve, often for many years. Living bacterial endospores that are thousands of years old have been recovered from Egyptian mummies!

Figure 9 Cyanobacteria, or blue-green algae, create an "algal bloom."

Research This

Biofilms

Skills: Researching, Analyzing, Evaluating

SKILLS HANDBOOK A2.1, A5.1

Under certain conditions, some bacteria form large colonies that stick together and to surfaces, forming biofilms. Dental plaque is a familiar example of a biofilm. In this activity you will research the characteristics and roles of biofilms.

1. Use the Internet and other resources to find out why some bacteria form biofilms.
2. Research why forming these colonies is advantageous to bacteria.
3. Research why biofilms are of particular interest to humans.

A. How and why do biofilms form? T/I

B. What are some ecological roles and benefits of biofilms? T/I

C. What are examples of biofilms that are harmful or damaging to property? T/I

D. Why are biofilms of medical interest? T/I

GO TO NELSON SCIENCE

Bacterial Diseases

Bacteria are responsible for many diseases ranging in severity from minor ear infections, which affect individuals, to the bubonic plague wiped out entire populations. **Table 2** lists a few bacterial diseases and examples of species that cause them.

Some infectious bacteria cause disease by producing and releasing toxins. For example, botulism food poisoning is caused by the toxin released by the bacterium *Clostridium botulinum*, which grows in poorly preserved foods. The toxin, botulin, is one of the most poisonous substances known. Botulin causes muscle paralysis that can be fatal if the muscles that control breathing are affected.

Other bacteria contain toxic compounds that are not released unless the cell dies. These toxins have different effects depending on the bacterial species and site of infection. One example of this type of bacteria is the *E. coli* strain O157:H7. This strain causes severe food poisoning and was responsible for the water contamination tragedy in Walkerton, Ontario, in 2000. Unlike other *E. coli*, this deadly strain has an additional piece of DNA with instructions for making the toxin. Evidence strongly suggests that this is a case of horizontal gene transfer. The strain was created when DNA was transferred to *E. coli* from the bacteria *Shigella dysenteriae*, the cause of dysentery. Antibiotics are the most successful and widely used treatment of bacterial infections. With *E. coli* O157:H7, however, the deadly toxin is released when the cell dies. A dose of antibiotics can kill many of the bacteria at once, causing a dangerous amount of the toxin to be released.

Table 2 Human Bacterial Diseases

Disease	Bacteria species
cholera	*Vibrio cholerae*
diphtheria	*Corynebacterium diphtheriae*
Lyme disease	*Borrelia burgdorferi*
pertussis	*Bordetella pertussis*
Rocky Mountain spotted fever	*Rickettsia rickettsii*
scarlet fever	*Streptococcus pyogenes*
tetanus	*Clostridium tetani*

Antibiotics and Antibiotic Resistance

Prokaryotes and fungi are often in direct competition with each other for food and resources, and they produce antibiotic substances as a form of chemical warfare. Imagine a piece of fruit that has just fallen from a tree and come in contact with fungi and bacteria on the ground. Both types of microbes would benefit from the nutrients in the fruit. By producing and releasing an antibiotic into the surroundings, one of the microbes may be able to kill the other and get the fruit.

Antibiotics are immensely valuable to humans (**Figure 10**). By mass-producing a wide variety of antibiotics, we can often kill bacteria where they are unwanted. Unfortunately, though antibiotics have saved many millions of lives, they may not be so effective in the future. The overuse of antibiotics can cause bacteria to adapt and become resistant, so that the antibiotics are no longer effective (**Figure 11**).

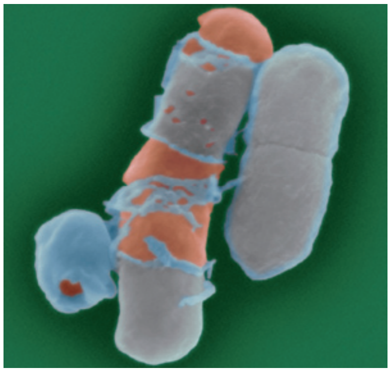

Figure 10 Penicillin killed the bacterium on the left by weakening its cell wall.

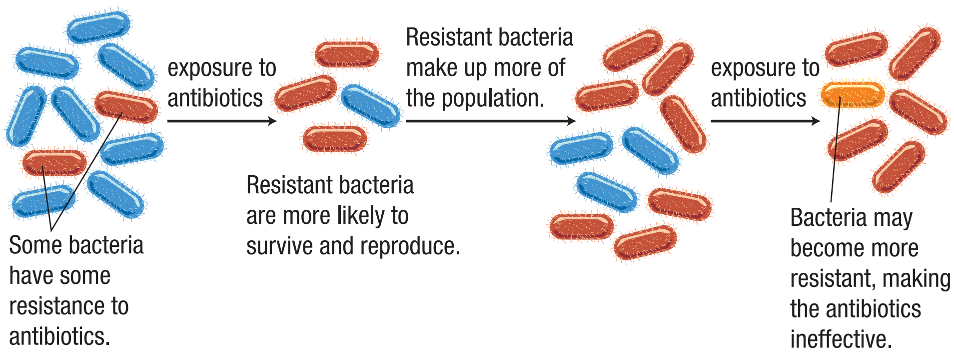

Figure 11 The process by which many bacteria develop antibiotic resistance

The Domain Archaea

Archaea are fascinating organisms, although little is known about them. These tiny prokaryotes were originally thought of as unusual types of true bacteria. They are now known to be unlike any other living thing. Their cell membranes and walls have a unique chemical makeup, and most lack peptidoglycan. Archaea also have genetic information that distinguishes them from bacteria and eukaryotes.

Figure 12 The sulfur-rich water of Emerald Hole in Yellowstone National Park has very high temperatures. Archaea can use foul smelling H_2S as a food source in this environment.

One characteristic of archaea is that many inhabit extreme environments (**Figure 12**). Some can even survive being boiled in strong detergents! Their cell membranes and cell walls are much more resistant to physical and chemical disruptions than those of other organisms.

There are three branches in Domain Archaea (see Figure 4, page 47). **Table 3** describes some examples of archaea from the group Euryarchaeota and highlights the diversity of organisms in this domain.

Table 3 Representative Archaea from the Group Euryarchaeota

Euryarchaeota subgroup	Key features

methanogens	• They live in low-oxygen environments, including
	  • sediments of swamps, lakes, marshes, and sewage lagoons
	  • digestive tracts of some mammals (including humans) and some insects
	• They generate energy by converting chemical compounds into methane gas, which is released into the atmosphere.

halophiles	• They are salt-loving organisms that can live in highly saline environments including the Dead Sea and foods preserved by salting. • Most are aerobic and get energy from organic food molecules. • Some use light as a secondary energy source.
extreme thermophiles	• They live in extremely hot environments including hot springs and hydrothermal vents on the ocean floor. • Their optimal temperature range for growth is 70 °C to 95 °C.
psychrophiles	• They are cold-loving organisms found mostly in the Antarctic and Arctic oceans, and cold ocean depths. • Their optimal temperature range for growth is −10 °C to −20 °C.

Research This

Prokaryotes and Environmental Change

Skills: Researching, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1, A5.1**

Organisms as small as prokaryotes can be influenced by environmental changes. For example, some bacterial diseases may be able to spread more effectively in warmer climates. Prokaryotes might also be useful in combating environmental change and damage. For example, cyanobacteria might be used to mass-produce a "green" source of fuel. In this activity you will work with a partner to research prokaryotes and environmental change.

1. Work with a partner. Decide who will research a possible effect of environmental change on a prokaryote and who will research a possible use of prokaryotes to protect the environment.
2. Conduct some initial research to find one or two examples that interest you. Check your choices with your teacher before continuing your research.
3. If you have chosen an effect of environmental change, conduct research about the following topics:
   (i) the nature and cause of the environmental change
   (ii) the ways in which the environmental change is affecting the organism
   (iii) the likely consequences of the effects on the organism, including how other species may be affected
4. If you have chosen to research a beneficial use of a prokaryote, conduct research about the following topics:
   (i) the characteristics of the prokaryote
   (ii) the benefits that the prokaryote provides or could provide
   (iii) the current status of technology

A. Share your summarized findings with your partner. T/I A

B. Share your findings with the class. Discuss the overall relationship between environmental change and prokaryotes. T/I A

GO TO NELSON SCIENCE

2.1 Summary

- Bacteria are extremely abundant and play keys roles in ecosystems as producers, decomposers, and pathogens.
- Bacteria are used in the production of some types of antibiotics and many different foods.
- Bacteria are characterized by the presence of peptidoglycan in their cell walls and have diverse metabolic processes.
- Bacteria reproduce asexually by binary fission and increase their genetic diversity by conjugation and transformation.
- The ability of bacteria to develop antibiotic resistance is a serious concern.
- Archaea are an important but not well understood group of prokaryotes.
- Archaea are found in a variety of habitats including many extreme environments and the intestines of mammals.
- Archaea have unique cell membranes, cell walls, and genetic information.

Investigation 2.1.1

Observing Bacteria (page 68)
Now that you have read about the different types of bacteria, you can complete Investigation 2.1.1.

In this observational study you will observe and identify basic types of bacteria and document your findings with biological drawings.

2.1 Questions

1. List three ways in which prokaryotes are important to humans and the environment. K/U
2. Which major groups of eubacteria perform photosynthesis? Which group uses a form of photosynthesis most similar to plants? K/U
3. Describe and state the function of each of the following: K/U
   (a) nucleoid
   (b) pili
   (c) plasmid
   (d) peptidoglycan
   (e) capsule
   (f) endospore
4. Create labelled sketches of the three common shapes of bacterial cells. K/U C
5. Distinguish between the following terms: K/U
   (a) inorganic and organic chemicals
   (b) obligate and facultative aerobes
   (c) conjugation and transformation
6. Conduct research to determine how the botulin toxin, released by *Clostridium botulinum*, is used in the cosmetics industry. What are the benefits and risks of this use? T/I A
7. Explain the role horizontal gene transfer is thought to have played in making the *E. coli* strain 0157:H7 so dangerous. K/U
8. What is the benefit to one kind of bacteria of producing antibiotics that kill other types of bacteria? K/U
9. (a) Describe the process by which many bacteria have developed resistance to antibiotics.
   (b) How has their ability to reproduce rapidly influenced this process? K/U T/I A
10. Describe two examples of symbiosis involving bacteria. K/U
11. Many genetic technologies rely on the ability to make copies of DNA molecules in the laboratory. This involves using chemicals that operate at high temperatures without being altered or destroyed. One of these chemicals is produced by the bacterium *Thermus thermophilus*. T/I A
    (a) Do you predict this bacterium to live in cold, moderate, or hot environments?
    (b) Conduct research to check your prediction. Were you correct? Where are these bacteria found in nature?
12. Describe three extreme environments that are inhabited by archaea. A
13. Although bacteria are typically unicellular, one group, the Myxobacteria, or "slime bacteria," form colonies containing millions of cells (**Figure 13**). Conduct research to determine how these bacteria benefit from forming such large associations. T/I

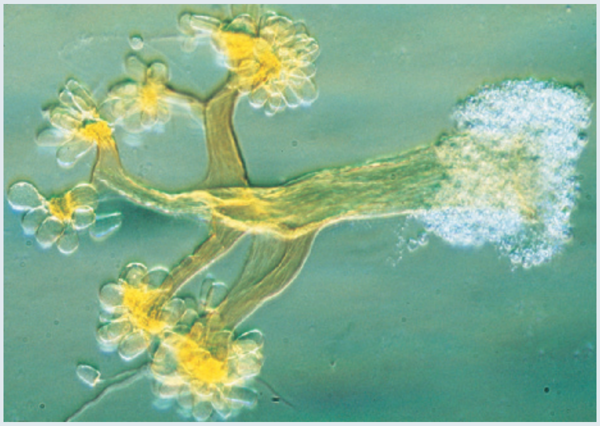

Figure 13 Colonies of Myxobacteria can contain millions of cells.

14. Imagine that you overheard someone say, "Bacteria cause disease. It would be good if we could eliminate all bacteria on Earth." Would you agree with this statement? Explain your reasoning. T/I A
15. Certain species of bacteria are the only organisms known to be able to feed on crude oil. These bacteria play an important role in cleaning up major oil spills. Use the Internet and other sources to find out more about these bacteria. How are these species used? How do they clean up oil spills? Do they occur naturally, or are they applied to the spill by clean-up crews? T/I A

GO TO NELSON SCIENCE