22.2: Structure of Prokaryotes

Skills to Develop

- Describe the basic structure of a typical prokaryote
- Describe important differences in structure between Archaea and Bacteria

There are many differences between prokaryotic and eukaryotic cells. However, all cells have four common structures: the plasma membrane, which functions as a barrier for the cell and separates the cell from its environment; the cytoplasm, a jelly-like substance inside the cell; nucleic acids, the genetic material of the cell; and ribosomes, where protein synthesis takes place. Prokaryotes come in various shapes, but many fall into three categories: cocci (spherical), bacilli (rod-shaped), and spirilli (spiral-shaped) (Figure \(\PageIndex{1}\)).

![Prokaryotes](https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/5%3A_Biol…

Figure \(\PageIndex{1}\): Prokaryotes fall into three basic categories based on their shape, visualized here using scanning electron microscopy: (a) cocci, or spherical (a pair is shown); (b) bacilli, or rod-shaped; and (c) spirilli, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox; scale-bar data from Matt Russell)
The Prokaryotic Cell

Recall that prokaryotes (Figure \(\PageIndex{2}\)) are unicellular organisms that lack organelles or other internal membrane-bound structures. Therefore, they do not have a nucleus but instead generally have a single chromosome—a piece of circular, double-stranded DNA located in an area of the cell called the nucleoid. Most prokaryotes have a cell wall outside the plasma membrane.

Figure \(\PageIndex{2}\): The features of a typical prokaryotic cell are shown.

Recall that prokaryotes are divided into two different domains, Bacteria and Archaea, which together with Eukarya, comprise the three domains of life (Figure \(\PageIndex{3}\)).

Figure \(\PageIndex{3}\): Bacteria and Archaea are both prokaryotes but differ enough to be placed in separate domains. An ancestor of modern Archaea is believed to have given rise to Eukarya, the third domain of life. Archaeal
and bacterial phyla are shown; the evolutionary relationship between these phyla is still open to debate.

The composition of the cell wall differs significantly between the domains Bacteria and Archaea. The composition of their cell walls also differs from the eukaryotic cell walls found in plants (cellulose) or fungi and insects (chitin). The cell wall functions as a protective layer, and it is responsible for the organism’s shape. Some bacteria have an outer capsule outside the cell wall. Other structures are present in some prokaryotic species, but not in others (Table \(\PageIndex{1}\)). For example, the capsule found in some species enables the organism to attach to surfaces, protects it from dehydration and attack by phagocytic cells, and makes pathogens more resistant to our immune responses. Some species also have flagella (singular, flagellum) used for locomotion, and pili (singular, pilus) used for attachment to surfaces. Plasmids, which consist of extra-chromosomal DNA, are also present in many species of bacteria and archaea.

Characteristics of phyla of Bacteria are described in Figure \(\PageIndex{4}\) and Figure \(\PageIndex{5}\); Archaea are described in Figure \(\PageIndex{6}\).

<table>
<thead>
<tr>
<th>Bacteria of Phylum Proteobacteria</th>
<th>Representative organisms</th>
<th>Representative micrograph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha Proteobacteria</td>
<td>Rhizobium</td>
<td>Rhizobium radiobacter, stained red, grows inside a host cell.</td>
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<tr>
<td></td>
<td>Nitrobacter</td>
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<td></td>
<td>Clostridium</td>
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<tr>
<td>Beta Proteobacteria</td>
<td>Nitrosomonas</td>
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<tr>
<td></td>
<td>Desulfovibrio</td>
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<tr>
<td>Gamma Proteobacteria</td>
<td>Escherichia coli</td>
<td>Vibrio cholera</td>
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<td></td>
<td>Salmonella</td>
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<td>Yersinia</td>
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<td>Volesella</td>
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<tr>
<td>Delta Proteobacteria</td>
<td>Microbacteriaceae</td>
<td>Desulfobulbus vulgaris</td>
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<tr>
<td></td>
<td>Desulfovirgula</td>
<td></td>
</tr>
<tr>
<td>Epsilon Proteobacteria</td>
<td>Campylobacter</td>
<td>Campylobacter</td>
</tr>
<tr>
<td></td>
<td>Helicobacter pylori</td>
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</tbody>
</table>

Figure \(\PageIndex{4}\): Phylum Proteobacteria is one of up to 52 bacteria phyla. Proteobacteria is further subdivided into five classes, Alpha through Epsilon. (credit “Rickettsia rickettsia”: modification of work by CDC; credit “Spirillum minus”: modification of work by Wolfram Adlassnig; credit “Vibrio cholera”: modification of work by Janice Haney Carr, CDC; credit “Desulfovibrio vulgaris”: modification of work by Graham Bradley; credit “Campylobacter”: modification of work by De Wood, Pooley, USDA, ARS, EMU; scale-bar data from Matt Russell)
<table>
<thead>
<tr>
<th>Bacteria: Chlamydia, Spirochetes, Cyanobacteria, and Gram-positive</th>
<th>Phyllum</th>
<th>Representative organisms</th>
<th>Representative micrograph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chlamydia</strong>&lt;br&gt;All members of this group are obligate intracellular parasites of animal cells. Cells lack peptidoglycan.</td>
<td>Chlamydia trachomatis&lt;br&gt;Common sexually transmitted disease that can lead to blindness</td>
<td>In this panel view, Chlamydia trachomatis appear as pink inclusions inside cells.</td>
<td></td>
</tr>
<tr>
<td><strong>Spirochetes</strong>&lt;br&gt;Most members of this species, which has spiral-shaped cells, are free-living amoebae, but some are parasitic. Many species are pathogenic. Spirochetes are found in the periplasmic spaces between the inner and outer membrane.</td>
<td>Treponema pallidum&lt;br&gt;Causative agent of syphilis&lt;br&gt;Borrelia burgdorferi&lt;br&gt;Causative agent of Lyme disease</td>
<td>Treponema pallidum</td>
<td></td>
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<tr>
<td><strong>Cyanobacteria</strong>&lt;br&gt;Also known as blue-green algae, these bacteria obtain their energy through photosynthesis. Cyanobacteria are found in terrestrial, marine, and freshwater environments. Exopolytic microalgae are thought to be bacteria in this group.</td>
<td>Prochlorococcus&lt;br&gt;Believed to be among the most abundant photosynthetic organisms on Earth, responsible for generating half the world’s oxygen.</td>
<td>Prochlorococcus</td>
<td></td>
</tr>
<tr>
<td><strong>Gram-positive Bacteria</strong>&lt;br&gt;Stalk-dwelling members of this subgroup give rise to many species that cause disease. They have a thick cell wall and lack an outer membrane.</td>
<td>Bacillus anthracis&lt;br&gt;Causes anthrax&lt;br&gt;Staphylococcus aureus&lt;br&gt;Causes Staphylococcal infection&lt;br&gt;Clostridium tetani&lt;br&gt;Causes tetanus&lt;br&gt;Clostridium difficile&lt;br&gt;Causes diarrhea during antibiotic therapy&lt;br&gt;Streptococcus&lt;br&gt;Main enteric bacteria, including streptococci, are derived from these bacteria.&lt;br&gt;Yersinia enterocolitica&lt;br&gt;These tiny bacteria, the smallest known, lack a cell wall and are free-living, and some are pathogenic.</td>
<td>Clostridium tetani</td>
<td></td>
</tr>
</tbody>
</table>

**Figure (PageIndex(5))**: Chlamydia, Spirochetes, Cyanobacteria, and Gram-positive bacteria are described in this table. Note that bacterial shape is not phylum-dependent; bacteria within a phylum may be cocci, rod-shaped, or spiral. (credit “Chlamydia trachomatis”: modification of work by Dr. Lance Liotta Laboratory, NCI; credit “Treponema pallidum”: modification of work by Dr. David Cox, CDC; credit “Phormidium”: modification of work by USGS; credit “Clostridium difficile”: modification of work by Lois S. Wiggs, CDC; scale-bar data from Matt Russell)
Archaea

<table>
<thead>
<tr>
<th>Phylum</th>
<th>Representative organisms</th>
<th>Representative micrograph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euryarchaeota</td>
<td>This phylum includes methanogens, which produce methane as a metabolic waste product, and halobacteria, which live in an extremely saline environment. Methanogenesis: Membrane production causes flammability in humans and other animals.</td>
<td></td>
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<td></td>
<td>Halobacteria: Large members of this halotolerant archaea appear red-brown due to the presence of halorhodopsin in the membrane. Bacteriorhodopsin is related to the retinal pigment rhodopsin.</td>
<td><img src="https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/5%3A_Biol%E2%80%A6" alt="Halobacterium" /></td>
</tr>
<tr>
<td>Crenarchaeota</td>
<td>Members of the ubiquitous phylum play an important role in the formation of carbon. Many members of this group are extremophiles and some are extremophiles or hyperthermophiles.</td>
<td><img src="https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/5%3A_Biol%E2%80%A6" alt="Subulohydrogenocapsa" /></td>
</tr>
<tr>
<td>Nanoarchaeota</td>
<td>This group contains only one species: <em>Nanoarchaeum equitans</em>. <em>Nanoarchaeum equitans</em>: This species was isolated from the bottom of the Atlantic Ocean and from a hydrothermal vent at Yellowstone National Park. It is an obligate symbiont with <em>thermobacterium</em>, another species of archaea.</td>
<td><img src="https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/5%3A_Biol%E2%80%A6" alt="Nanoarchaeum" /></td>
</tr>
<tr>
<td>Korarchaeota</td>
<td>Members of this phylum, considered to be one of the most primitive forms of life, have only been found in the Oligocene fossil in Yellowstone National Park.</td>
<td><img src="https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_General_Biology_(OpenStax)/5%3A_Biol%E2%80%A6" alt="Korarchaeota" /></td>
</tr>
</tbody>
</table>

Figure \(\PageIndex{6}\): Archaea are separated into four phyla: the Korarchaeota, Euryarchaeota, Crenarchaeota, and Nanoarchaeota. (credit “Halobacterium”: modification of work by NASA; credit “Nanoarchaeotum equitans”: modification of work by Karl O. Stetter; credit “korarchaeota”: modification of work by Office of Science of the U.S. Dept. of Energy; scale-bar data from Matt Russell)

**The Plasma Membrane**

The plasma membrane is a thin lipid bilayer (6 to 8 nanometers) that completely surrounds the cell and separates the inside from the outside. Its selectively permeable nature keeps ions, proteins, and other molecules within the cell and prevents them from diffusing into the extracellular environment, while other molecules may move through the membrane. Recall that the general structure of a cell membrane is a phospholipid bilayer composed of two layers of lipid molecules. In archaenal cell membranes, isoprene (phytanyl) chains linked to glycerol replace the fatty acids linked to glycerol in bacterial membranes. Some archaenal membranes are lipid monolayers instead of bilayers (Figure \(\PageIndex{7}\)).
Archaeal phospholipids differ from those found in Bacteria and Eukarya in two ways. First, they have branched phytanyl sidechains instead of linear ones. Second, an ether bond instead of an ester bond connects the lipid to the glycerol.

The Cell Wall

The cytoplasm of prokaryotic cells has a high concentration of dissolved solutes. Therefore, the osmotic pressure within the cell is relatively high. The cell wall is a protective layer that surrounds some cells and gives them shape and rigidity. It is located outside the cell membrane and prevents osmotic lysis (bursting due to increasing volume). The chemical composition of the cell walls varies between archaea and bacteria, and also varies between bacterial species.

Bacterial cell walls contain peptidoglycan, composed of polysaccharide chains that are cross-linked by unusual peptides containing both L- and D-amino acids including D-glutamic acid and D-alanine. Proteins normally have only L-amino acids; as a consequence, many of our antibiotics work by mimicking D-amino acids and therefore have specific effects on bacterial cell wall development. There are more than 100 different forms of peptidoglycan. S-layer (surface layer) proteins are also present on the outside of cell walls of both archaea and bacteria.

Bacteria are divided into two major groups: Gram positive and Gram negative, based on their reaction to Gram staining. Note that all Gram-positive bacteria belong to one phylum; bacteria in the other phyla (Proteobacteria, Chlamydias, Spirochetes, Cyanobacteria, and others) are Gram-negative. The Gram staining method is named after its inventor, Danish scientist Hans Christian Gram (1853–1938). The different bacterial responses to the staining procedure are ultimately due to cell wall structure. Gram-positive organisms typically lack the outer membrane found in Gram-negative organisms (Figure 

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the cell membrane. Gram-negative bacteria have a relatively thin cell wall composed of a few layers of peptidoglycan (only 10 percent of the total cell wall), surrounded by an outer envelope containing lipopolysaccharides (LPS) and lipoproteins. This outer envelope is sometimes referred to as a second lipid bilayer. The chemistry of this outer envelope is very different, however, from that of the typical lipid bilayer that forms plasma membranes.

Art Connection

Figure (PageIndex{8}): Bacteria are divided into two major groups: Gram positive and Gram negative. Both groups have a cell wall composed of peptidoglycan: in Gram-positive bacteria, the wall is thick, whereas in Gram-negative bacteria, the wall is thin. In Gram-negative bacteria, the cell wall is surrounded by an outer membrane that contains lipopolysaccharides and lipoproteins. Porins are proteins in this cell membrane that allow substances to pass through the outer membrane of Gram-negative bacteria. In Gram-positive bacteria, lipoteichoic acid anchors the cell wall to the cell membrane. (credit: modification of work by "Franciscosp2"/Wikimedia Commons)

Which of the following statements is true?

1. Gram-positive bacteria have a single cell wall anchored to the cell membrane by lipoteichoic acid.
2. Porins allow entry of substances into both Gram-positive and Gram-negative bacteria.
3. The cell wall of Gram-negative bacteria is thick, and the cell wall of Gram-positive bacteria is thin.
4. Gram-negative bacteria have a cell wall made of peptidoglycan, whereas Gram-positive bacteria have a cell wall made of lipoteichoic acid.

Archaeal cell walls do not have peptidoglycan. There are four different types of Archaeal cell walls. One type is composed of pseudopeptidoglycan, which is similar to peptidoglycan in morphology but contains different sugars in the polysaccharide chain. The other three types of cell walls are composed of polysaccharides, glycoproteins, or pure protein.

Table (PageIndex{1}): Structural Differences and Similarities between Bacteria and Archaea

<table>
<thead>
<tr>
<th>Structural Characteristic</th>
<th>Bacteria</th>
<th>Archaea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell type</td>
<td>Prokaryotic</td>
<td>Prokaryotic</td>
</tr>
<tr>
<td>Cell morphology</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Cell wall</td>
<td>Contains peptidoglycan</td>
<td>Does not contain peptidoglycan</td>
</tr>
<tr>
<td>Cell membrane type</td>
<td>Lipid bilayer</td>
<td>Lipid bilayer or lipid monolayer</td>
</tr>
</tbody>
</table>
Reproduction

Reproduction in prokaryotes is asexual and usually takes place by binary fission. Recall that the DNA of a prokaryote exists as a single, circular chromosome. Prokaryotes do not undergo mitosis. Rather the chromosome is replicated and the two resulting copies separate from one another, due to the growth of the cell. The prokaryote, now enlarged, is pinched inward at its equator and the two resulting cells, which are clones, separate. Binary fission does not provide an opportunity for genetic recombination or genetic diversity, but prokaryotes can share genes by three other mechanisms.

In transformation, the prokaryote takes in DNA found in its environment that is shed by other prokaryotes. If a nonpathogenic bacterium takes up DNA for a toxin gene from a pathogen and incorporates the new DNA into its own chromosome, it too may become pathogenic. In transduction, bacteriophages, the viruses that infect bacteria, sometimes also move short pieces of chromosomal DNA from one bacterium to another. Transduction results in a recombinant organism. Archaea are not affected by bacteriophages but instead have their own viruses that translocate genetic material from one individual to another. In conjugation, DNA is transferred from one prokaryote to another by means of a pilus, which brings the organisms into contact with one another. The DNA transferred can be in the form of a plasmid or as a hybrid, containing both plasmid and chromosomal DNA. These three processes of DNA exchange are shown in Figure ~(Figure 9)~.

Reproduction can be very rapid: a few minutes for some species. This short generation time coupled with mechanisms of genetic recombination and high rates of mutation result in the rapid evolution of prokaryotes, allowing them to respond to environmental changes (such as the introduction of an antibiotic) very quickly.

*Figure ~(Figure 9)~: Besides binary fission, there are three other mechanisms by which prokaryotes can exchange DNA. In (a) transformation, the cell takes up prokaryotic DNA directly from the environment. The DNA may remain separate as plasmid DNA or be incorporated into the host genome. In (b) transduction, a bacteriophage injects DNA into the cell that contains a small fragment of DNA from a different prokaryote. In (c) conjugation, DNA is transferred from one cell to another via a mating bridge that connects the two cells after the sex pilus draws the two bacteria close enough to form the bridge.*

Evolution Connection: The Evolution of Prokaryotes
How do scientists answer questions about the evolution of prokaryotes? Unlike with animals, artifacts in the fossil record of prokaryotes offer very little information. Fossils of ancient prokaryotes look like tiny bubbles in rock. Some scientists turn to genetics and to the principle of the molecular clock, which holds that the more recently two species have diverged, the more similar their genes (and thus proteins) will be. Conversely, species that diverged long ago will have more genes that are dissimilar.

Scientists at the NASA Astrobiology Institute and at the European Molecular Biology Laboratory collaborated to analyze the molecular evolution of 32 specific proteins common to 72 species of prokaryotes. The model they derived from their data indicates that three important groups of bacteria—Actinobacteria, Deinococcus, and Cyanobacteria (which the authors call Terrabacteria)—were the first to colonize land. (Recall that Deinococcus is a genus of prokaryote—a bacterium—that is highly resistant to ionizing radiation.) Cyanobacteria are photosynthesizers, while Actinobacteria are a group of very common bacteria that include species important in decomposition of organic wastes.

The timelines of divergence suggest that bacteria (members of the domain Bacteria) diverged from common ancestral species between 2.5 and 3.2 billion years ago, whereas archaea diverged earlier: between 3.1 and 4.1 billion years ago. Eukarya later diverged off the Archaean line. The work further suggests that stromatolites that formed prior to the advent of cyanobacteria (about 2.6 billion years ago) photosynthesized in an anoxic environment and that because of the modifications of the Terrabacteria for land (resistance to drying and the possession of compounds that protect the organism from excess light), photosynthesis using oxygen may be closely linked to adaptations to survive on land.

Summary

Prokaryotes (domains Archaea and Bacteria) are single-celled organisms lacking a nucleus. They have a single piece of circular DNA in the nucleoid area of the cell. Most prokaryotes have a cell wall that lies outside the boundary of the plasma membrane. Some prokaryotes may have additional structures such as a capsule, flagella, and pili. Bacteria and Archaea differ in the lipid composition of their cell membranes and the characteristics of the cell wall. In archaeal membranes, phytanyl units, rather than fatty acids, are linked to glycerol. Some archaeal membranes are lipid monolayers instead of bilayers.

The cell wall is located outside the cell membrane and prevents osmotic lysis. The chemical composition of cell walls varies between species. Bacterial cell walls contain peptidoglycan. Archaean cell walls do not have peptidoglycan, but they may have pseudopeptidoglycan, polysaccharides, glycoproteins, or protein-based cell walls. Bacteria can be divided into two major groups: Gram positive and Gram negative, based on the Gram stain reaction. Gram-positive organisms have a thick cell wall, together with teichoic acids. Gram-negative organisms have a thin cell wall and an outer envelope containing lipopolysaccharides and lipoproteins.

Art Connections

Which of the following statements is true?

1. Gram-positive bacteria have a single cell wall anchored to the cell membrane by lipoteichoic acid.
2. Porins allow entry of substances into both Gram-positive and Gram-negative bacteria.
3. The cell wall of Gram-negative bacteria is thick, and the cell wall of Gram-positive bacteria is thin.
4. Gram-negative bacteria have a cell wall made of peptidoglycan, whereas Gram-positive bacteria have a cell wall made of lipoteichoic acid.

Footnotes


Glossary

**capsule**
- external structure that enables a prokaryote to attach to surfaces and protects it from dehydration

**conjugation**
- process by which prokaryotes move DNA from one individual to another using a pilus

**Gram negative**
- bacterium whose cell wall contains little peptidoglycan but has an outer membrane

**Gram positive**
- bacterium that contains mainly peptidoglycan in its cell walls

**peptidoglycan**
- material composed of polysaccharide chains cross-linked to unusual peptides

**pilus**
- surface appendage of some prokaryotes used for attachment to surfaces including other prokaryotes

**pseudopeptidoglycan**
- component of archaea cell walls that is similar to peptidoglycan in morphology but contains different sugars

**S-layer**
- surface-layer protein present on the outside of cell walls of archaea and bacteria

**teichoic acid**
- polymer associated with the cell wall of Gram-positive bacteria

**transduction**
- process by which a bacteriophage moves DNA from one prokaryote to another

**transformation**
- process by which a prokaryote takes in DNA found in its environment that is shed by other prokaryotes

Contributors

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