Chapter 27
Bacteria and Archaea

Concept 27.1: Structural and functional adaptations contribute to prokaryotic success

- Earth’s first organisms were likely prokaryotes
- Most prokaryotes are unicellular, although some species form colonies
- Most prokaryotic cells are 0.5–5 µm, much smaller than the 10–100 µm of many eukaryotic cells
- Prokaryotic cells have a variety of shapes
- The three most common shapes are spheres (cocci), rods (bacilli), and spirals

Cell-Surface Structures

- An important feature of nearly all prokaryotic cells is their cell wall, which maintains cell shape, protects the cell, and prevents it from bursting in a hypotonic environment
- Bacterial cell walls contain peptidoglycan, a network of sugar polymers cross-linked by polypeptides
- Archaea contain polysaccharides and proteins but lack peptidoglycan

- Prokaryotes thrive almost everywhere, including places too acidic, salty, cold, or hot for most other organisms
- Most prokaryotes are microscopic, but what they lack in size they make up for in numbers
- There are more in a handful of fertile soil than the number of people who have ever lived
- Prokaryotes are divided into two domains: bacteria and archaea
Scientists use the **Gram stain** to classify bacteria by cell wall composition

- **Gram-positive** bacteria have simpler walls with a large amount of peptidoglycan
- **Gram-negative** bacteria have less peptidoglycan and an outer membrane that can be toxic
- Many antibiotics target peptidoglycan and damage bacterial cell walls
- Gram-negative bacteria are more likely to be antibiotic resistant

A polysaccharide or protein layer called a **capsule** covers many prokaryotes

Some prokaryotes have **fimbriae**, which allow them to stick to their substrate or other individuals in a colony

- **Pili** (or sex pili) are longer than fimbriae and allow prokaryotes to exchange DNA

**Motility**

- In a heterogeneous environment, many bacteria exhibit **taxis**, the ability to move toward or away from a stimulus
- Chemotaxis is the movement toward or away from a chemical stimulus
- Most motile bacteria propel themselves by flagella scattered about the surface or concentrated at one or both ends

Flagella of bacteria, archaea, and eukaryotes are composed of different proteins and likely evolved independently
Internal Organization and DNA

- Prokaryotic cells usually lack complex compartmentalization
- Some prokaryotes do have specialized membranes that perform metabolic functions
- These are usually infoldings of the plasma membrane

There are some differences between prokaryotes and eukaryotes in DNA replication, transcription, and translation
- These allow people to use some antibiotics to inhibit bacterial growth without harming themselves

Reproduction and Adaptation

- Prokaryotes reproduce quickly by binary fission and can divide every 1–3 hours
- Key features of prokaryotic reproduction:
  - They are small
  - They reproduce by binary fission
  - They have short generation times

Many prokaryotes form metabolically inactive endospores, which can remain viable in harsh conditions for centuries

The prokaryotic genome has less DNA than the eukaryotic genome
- Most of the genome consists of a circular chromosome
- The chromosome is not surrounded by a membrane; it is located in the nucleoid region
- Some species of bacteria also have smaller rings of DNA called plasmids

Their short generation time allows prokaryotes to evolve quickly
- For example, adaptive evolution in a bacterial colony was documented in a lab over 8 years
- Prokaryotes are not “primitive” but are highly evolved
Prokaryotes have considerable genetic variation.

Three factors contribute to this genetic diversity:

- Rapid reproduction
- Mutation
- Genetic recombination

**Concept 27.2: Rapid reproduction, mutation, and genetic recombination promote genetic diversity in prokaryotes**

**Rapid Reproduction and Mutation**

- Prokaryotes reproduce by binary fission, and offspring cells are generally identical.
- Mutation rates during binary fission are low, but because of rapid reproduction, mutations can accumulate rapidly in a population.
- High diversity from mutations allows for rapid evolution.

**Genetic Recombination**

- Genetic recombination, the combining of DNA from two sources, contributes to diversity.
- Prokaryotic DNA from different individuals can be brought together by transformation, transduction, and conjugation.
- Movement of genes among individuals from different species is called horizontal gene transfer.

**Transformation and Transduction**

- A prokaryotic cell can take up and incorporate foreign DNA from the surrounding environment in a process called transformation.
- Transduction is the movement of genes between bacteria by bacteriophages (viruses that infect bacteria).

![Figure 27.11-1](image1)

![Figure 27.11-2](image2)
Conjugation and Plasmids

- **Conjugation** is the process where genetic material is transferred between prokaryotic cells.
- In bacteria, the DNA transfer is one way.
- A donor cell attaches to a recipient by a pilus, pulls it closer, and transfers DNA.
- A piece of DNA called the **F factor** is required for the production of pili.

The F Factor as a Plasmid

- Cells containing the **F plasmid** function as DNA donors during conjugation.
- Cells without the F factor function as DNA recipients during conjugation.
- The F factor is transferable during conjugation.

The F Factor in the Chromosome

- A cell with the F factor built into its chromosomes functions as a donor during conjugation.
- The recipient becomes a recombinant bacterium, with DNA from two different cells.
Concept 27.3: Diverse nutritional and metabolic adaptations have evolved in prokaryotes

<table>
<thead>
<tr>
<th>Table 27.1 Major Nutritional Modes</th>
<th>Mode</th>
<th>Energy Source</th>
<th>Carbon Source</th>
<th>Types of Organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUTOTROPH</td>
<td>Photoautotroph</td>
<td>Light</td>
<td>CO₂, HCO₃⁻, or related compound</td>
<td>Photosynthetic prokaryotes (for example, cyanobacterial plants; certain protists (for example, algae))</td>
</tr>
<tr>
<td></td>
<td>Chemoheterotroph</td>
<td>Inorganic chemicals (such as H₂S, NH₃, or Fe³⁺⁺)</td>
<td>CO₂, HCO₃⁻, or related compound</td>
<td>Unique to certain prokaryotes (for example, Sulfobacter)</td>
</tr>
<tr>
<td>HETEROTROPH</td>
<td>Photoheterotroph</td>
<td>Light</td>
<td>Organic compounds</td>
<td>Unique to certain aquatic and soil-living prokaryotes (for example, Rhodobacter, Chloroflexus)</td>
</tr>
<tr>
<td></td>
<td>Chemoheterotroph</td>
<td>Organic compounds</td>
<td>Organic compounds</td>
<td>Many prokaryotes (for example, Clostridium) and protists (fungi, animals, some plants)</td>
</tr>
</tbody>
</table>

The Role of Oxygen in Metabolism

- Prokaryotic metabolism varies with respect to O₂
  - **Obligate aerobes** require O₂ for cellular respiration
  - **Obligate anaerobes** are poisoned by O₂ and use fermentation or anaerobic respiration
  - **Facultative anaerobes** can survive with or without O₂

Nitrogen Metabolism

- Nitrogen is essential for the production of amino acids and nucleic acids
- Prokaryotes can metabolize nitrogen in a variety of ways
- In **nitrogen fixation**, some prokaryotes convert atmospheric nitrogen (N₂) to ammonia (NH₃)

Metabolic Cooperation

- Cooperation between prokaryotes allows them to use environmental resources they could not use as individual cells
- In the cyanobacterium **Anabaena**, photosynthetic cells and nitrogen-fixing cells called **heterocysts** (or heterocytes) exchange metabolic products

R Plasmids and Antibiotic Resistance

- **R plasmids** carry genes for antibiotic resistance
- Antibiotics kill sensitive bacteria, but not bacteria with specific R plasmids
- Through natural selection, the fraction of bacteria with genes for resistance increases in a population exposed to antibiotics
- Antibiotic-resistant strains of bacteria are becoming more common
In some prokaryotic species, metabolic cooperation occurs in surface-coating colonies called **biofilms**

**Figure 27.14 Dental plaque**

**Concept 27.4: Molecular systematics is illuminating prokaryotic phylogeny**

- Until the late 20th century, systematists based prokaryotic taxonomy on phenotypic criteria
- Applying molecular systematics to the investigation of prokaryotic phylogeny has produced dramatic results

**Lessons from Molecular Systematics**

- The use of polymerase chain reaction (PCR) has allowed for more rapid sequencing of prokaryote genomes
- A handful of soil may contain 10,000 prokaryotic species
- Horizontal gene transfer between prokaryotes obscures the root of the tree of life

**Archaea**

- Archaea share certain traits with bacteria and other traits with eukaryotes

**Table 27.3 A Comparison of the Three Domains of Life**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Bacteria</th>
<th>Archaea</th>
<th>Eukarya</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear envelope</td>
<td>Absent</td>
<td>Absent</td>
<td>Present</td>
</tr>
<tr>
<td>Membrane-enclosed organelles</td>
<td>Absent</td>
<td>Absent</td>
<td>Present</td>
</tr>
<tr>
<td>Peptidoglycan in cell wall</td>
<td>Present</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Membrane lipids</td>
<td>Unbranched hydrocarbons</td>
<td>Some branched hydrocarbons</td>
<td>Unbranched hydrocarbons</td>
</tr>
<tr>
<td>RNA polymerase</td>
<td>One kind</td>
<td>Several kinds</td>
<td>Several kinds</td>
</tr>
<tr>
<td>Initiator amino acid for protein synthesis</td>
<td>Formyl-methionine</td>
<td>Methionine</td>
<td>Methionine</td>
</tr>
<tr>
<td>Introns in genes</td>
<td>Very rare</td>
<td>Present in some genes</td>
<td>Present in many genes</td>
</tr>
<tr>
<td>Response to the antibiotics streptomycin and chloramphenicol</td>
<td>Growth inhibited</td>
<td>Growth not inhibited</td>
<td>Growth not inhibited</td>
</tr>
<tr>
<td>Histones associated with DNA</td>
<td>Absent</td>
<td>Present in some species</td>
<td>Present</td>
</tr>
<tr>
<td>Circular chromosome</td>
<td>Present</td>
<td>Present</td>
<td>Absent</td>
</tr>
<tr>
<td>Growth at temperatures ≤ 100°C</td>
<td>No</td>
<td>Some species</td>
<td>No</td>
</tr>
</tbody>
</table>
• Some archaea live in extreme environments and are called extremophiles
  • Extreme halophiles live in highly saline environments
  • Extreme thermophiles thrive in very hot environments

• Methanogens live in swamps and marshes and produce methane as a waste product
  • Methanogens are strict anaerobes and are poisoned by \( O_2 \)
  • In recent years, genetic prospecting has revealed many new groups of archaea

Clades
• Euryarcheota: many extreme halophiles, all known methanogens and some thermophiles
• Crenarcheota: most of thermophiles
• Korarchaeota: primitive thermophilic organisms that do not belong to either two clades above
• Nanoarchaeota: nanosized hyperthermophilic symbiont

Bacteria
• Bacteria include the vast majority of prokaryotes of which most people are aware
• Diverse nutritional types are scattered among the major groups of bacteria
  – Proteobacteria
  – Chlamydiias
  – Spirochetes
  – Cyanobacteria
  – Gram-Positive Bacteria

Proteobacteria
• These gram-negative bacteria include photoautotrophs, chemoautotrophs, and heterotrophs
• Some are anaerobic, and others aerobic
• Include subgroups: alpha, beta, gamma, delta and epsilon

• Many species are closely associated with eukaryotic hosts
• Scientists hypothesize that mitochondria evolved from aerobic alpha proteobacteria through endosymbiosis
• Example: the soil bacterium Nitrosomonas, which converts NH$_4^+$ to NO$_2^-$

Subgroup: Beta Proteobacteria

Nitrosomonas (colorized TEM)

• Examples include sulfur bacteria such as Chromatium and pathogens such as Legionella, Salmonella, and Vibrio cholerae

Subgroup: Gamma Proteobacteria

Thiomargarita namibiensis containing sulfur wastes (LM)

• Escherichia coli resides in the intestines of many mammals and is not normally pathogenic

• Example: the slime-secreting myxobacteria

Subgroup: Delta Proteobacteria

Fruiting bodies of Chondromyces crocatus, a myxobacterium (SEM)

• This group contains many pathogens including Campylobacter, which causes blood poisoning, and Helicobacter pylori, which causes stomach ulcers

Subgroup: Epsilon Proteobacteria

Helicobacter pylori (colorized TEM)

Chlamydias

• These bacteria are parasites that live within animal cells

• Chlamydia trachomatis causes blindness and nongonococcal urethritis by sexual transmission

Subgroup: Chlamydia

Chlamydia (arrows) inside an animal cell (colorized TEM)

Spirochetes

• These bacteria are helical heterotrophs

• Some are parasites, including Treponema pallidum, which causes syphilis, and Borrelia burgdorferi, which causes Lyme disease

Subgroup: Spirochetes

Treponema pallidum

Borrelia burgdorferi
Cyanobacteria

- These are photoautotrophs that generate O$_2$
- Plant chloroplasts likely evolved from cyanobacteria by the process of endosymbiosis

Gram-Positive Bacteria

- Actinomycetes, which decompose soil
- Bacillus anthracis, the cause of anthrax
- Clostridium botulinum, the cause of botulism
- Some Staphylococcus and Streptococcus, which can be pathogenic
- Mycoplasms, the smallest known cells

Concept 27.5: Prokaryotes play crucial roles in the biosphere

- Prokaryotes are so important that if they were to disappear the prospects for any other life surviving would be dim

Chemical Recycling

- Prokaryotes play a major role in the recycling of chemical elements between the living and nonliving components of ecosystems
- Chemoheterotrophic prokaryotes function as decomposers, breaking down dead organisms and waste products

Ecological Interactions

- Symbiosis is an ecological relationship in which two species live in close contact: a larger host and smaller symbiont
- Prokaryotes often form symbiotic relationships with larger organisms
- In commensalism, one organism benefits while neither harming nor helping the other in any significant way

- In mutualism, both symbiotic organisms benefit. The bacteria receive nutrients from this flashlight fish. The fish uses the light generated by the bioluminescent bacteria to attract prey and signal potential mates
In parasitism, an organism called a parasite harms but does not kill its host.
Parasites that cause disease are called pathogens.
The ecological communities of hydrothermal vents depend on chemoautotrophic bacteria for energy.

Mutualistic Bacteria
- Human intestines are home to about 500–1,000 species of bacteria.
- Many of these are mutualists and break down food that is undigested by our intestines.

Pathogenic Bacteria
- Prokaryotes cause about half of all human diseases.
- Pathogenic prokaryotes typically cause disease by releasing exotoxins or endotoxins.
- Exotoxins are secreted and cause disease even if the prokaryotes that produce them are not present.
- Endotoxins are released only when bacteria die and their cell walls break down.

Prokaryotes in Research and Technology
- Experiments using prokaryotes have led to important advances in DNA technology.
  - For example, *E. coli* is used in gene cloning.
  - For example, *Agrobacterium tumefaciens* is used to produce transgenic plants.
- Bacteria can now be used to make natural plastics.

Concept 27.6: Prokaryotes have both beneficial and harmful impacts on humans
- Some prokaryotes are human pathogens, but others have positive interactions with humans.

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