Chapter 27

Bacteria and Archaea

Lecture Outline

Overview: Masters of Adaptation

- California's Owens Lake has a salt concentration of 32%, nine times saltier than seawater.
- Despite its harsh conditions, the lake's distinctive pink color is caused by **bacteriorhodopsin,** a photosynthetic pigment produced by trillions of *Halobacteria*, a single-celled archaean.
- This archaean is among the most salt-tolerant organisms on Earth. It pumps K^+ into its cell until the ionic concentration within the cell matches the external salt concentration.
- Many other prokaryotes are adapted to extremely harsh conditions.
  - *Deinococcus radiodurans* can survive a radiation dose of 3,000,000 rads, while 1000 rads is fatal to a human.
  - *Picrophilus oshimae* can grow at a pH of 0.03, acidic enough to dissolve metal.
  - Some prokaryotes live in rocks 3.2 kilometers below the Earth's surface.
- Prokaryotes are adapted to a broad range of habitats, including the land and waters in which other species are found.
- Today, prokaryotes still dominate the biosphere.
  - Their collective biomass outweighs that of all eukaryotes combined by at least tenfold.
  - More prokaryotes inhabit a handful of fertile soil or the mouth or skin of a human than the total number of people who have ever lived.

Concept 27.1 Structural and functional adaptations contribute to prokaryotic success.

Prokaryotes are small.

- Prokaryotes were the first organisms to live on Earth.
- Most prokaryotes are unicellular.
- Some species may aggregate transiently or permanently in colonies.
- Most prokaryotes have diameters in the range of 0.5–5 µm, compared to 10–100 µm for most eukaryotic cells.
  - The largest prokaryote discovered so far has a diameter of 750 µm, just visible to the unaided eye.
- The most common shapes among prokaryotes are spheres (cocci), rods (bacilli), and spirals.

Nearly all prokaryotes have a cell wall external to the plasma membrane.

- In nearly all prokaryotes, a cell wall maintains the shape of the cell, affords physical protection, and prevents the cell from bursting in a hypotonic environment.
- In a hypertonic environment, most prokaryotes lose water and plasmolyze, like other walled cells.
  - Severe water loss inhibits the reproduction of prokaryotes, which explains why salt can be used to preserve foods.
- Most bacterial cell walls contain **peptidoglycan,** a polymer of modified sugars cross-linked by short polypeptides.
  - This molecular fabric encloses the entire bacterium and anchors other molecules that extend from its surface.
  - The cell walls of archaea contain polysaccharides and proteins, but lack peptidoglycan.
- The **Gram stain** is a valuable tool for identifying specific bacteria based on differences in their cell walls.
  - **Gram-positive** bacteria have simple cell walls with large amounts of peptidoglycans.
  - **Gram-negative** bacteria have more complex cell walls with less peptidoglycan.
- An outer membrane on the cell wall of gram-negative cells contains lipopolysaccharides, carbohydrates bonded to lipids.
- Among pathogenic bacteria, gram-negative species are generally more deadly than gram-positive species.
  - The lipopolysaccharides on the walls of gram-negative bacteria are often toxic, and the outer membrane protects the pathogens from the defenses of their hosts.
  - Gram-negative bacteria are commonly more resistant than gram-positive species to antibiotics because the outer membrane impedes entry of the drugs.
- Many antibiotics, including penicillin, inhibit the synthesis of cross-links in peptidoglycans, preventing the formation of a functional wall, especially in gram-positive species.
  - These drugs cripple many species of bacteria, without affecting human and other eukaryote cells that do not synthesize peptidoglycans.
- Many prokaryotes secrete another sticky protective layer of polysaccharide or protein, the **capsule,** outside the cell wall.
  - Capsules allow cells to adhere to their substrate or to other individuals in a colony.
  - Some capsules protect against dehydration, and some may increase resistance to host defenses.
- Another way for prokaryotes to adhere to one another or to the substratum is by surface appendages called **fimbriae**, also known as *attachment pili***.**
  - Fimbriae are usually more numerous and shorter than **sex pili**.
  - Sex pili are specialized for holding two prokaryote cells together long enough to transfer DNA during conjugation.

Many prokaryotes are motile.

- About half of all prokaryotes are capable of directional movement.
  - Some species can move at speeds exceeding 50 µm/sec, about 50 times their body length per second.
- The beating of flagella scattered over the entire surface or concentrated at one or both ends is the most common method of movement.
  - The flagella of prokaryotes differ in structure and function from those of eukaryotes.

- In a heterogeneous environment, many prokaryotes are capable of **taxis,** movement *toward* nutrients or oxygen (positive chemotaxis) or *away from* a toxic substance (negative chemotaxis).
    - Prokaryotes that exhibit chemotaxis respond to chemicals by changing their movement patterns.
    - Solitary *Escherichia coli* may exhibit positive chemotaxis toward other members of their species, enabling the formation of colonies.

The cellular and genomic organization of prokaryotes is fundamentally different from that of eukaryotes.

- The cells of prokaryotes are simpler than those of eukaryotes in both internal structure and genomic organization.
- Prokaryotic cells lack the complex compartmentalization found in eukaryotic cells.
- Instead, prokaryotes use specialized infolded regions of the plasma membrane to perform many metabolic functions, including cellular respiration and photosynthesis.
- Prokaryotes have smaller, simpler genomes than eukaryotes.
- In the majority of prokaryotes, the genome consists of a ring of DNA with few associated proteins.
- The prokaryotic chromosome is located in the **nucleoid region**.
- Prokaryotes may also have smaller rings of DNA called **plasmids,** which consist of only a few genes.
- Although the general processes for DNA replication and translation of mRNA into proteins are fundamentally alike in eukaryotes and prokaryotes, some of the details differ.
    - For example, prokaryotic ribosomes are slightly smaller than the eukaryotic version and differ in protein and RNA content.
- These differences are great enough that selective antibiotics, including tetracycline and erythromycin, bind to prokaryotic ribosomes to block protein synthesis in prokaryotes but not in eukaryotes.

Populations of prokaryotes grow and adapt rapidly.

- Prokaryotes have the potential to reproduce quickly in a favorable environment.
    - While most prokaryotes have generation times of 1–3 hours, some species can produce a new generation in 20 minutes under optimal conditions.
    - A single cell in favorable conditions produces a large colony of offspring very quickly.
- Prokaryotes reproduce asexually via **binary fission,** synthesizing DNA almost continuously.
- Prokaryotic reproduction is limited because cells eventually exhaust their nutrient supply, accumulate metabolic wastes, face competition from other microbes, or are consumed by other organisms.
- Some bacteria form resistant cells called **endospores** when an essential nutrient is lacking in the environment.
    - A cell replicates its chromosome and surrounds one chromosome with a durable wall to form the endospore. Water is removed from the endospore, halting metabolism.
    - The original cell then disintegrates to leave the endospore behind.
- An endospore is resistant to all sorts of trauma.
    - Most endospores can survive in boiling water.

- Endospores may remain dormant but viable for centuries or longer.
- When the environment becomes more hospitable, the endospore absorbs water and resumes growth.
- Sterilization in an autoclave kills endospores by heating them to 121°C under high pressure.

- Mutation is the major source of genetic variation in prokaryotes.
- With generation times of minutes or hours, prokaryotic populations can adapt very rapidly to environmental changes as natural selection favors gene mutations that confer greater fitness.
- As a consequence, prokaryotes are important model organisms for scientists who study evolution in the laboratory.
- Prokaryotes are highly evolved. For more than 3.5 billion years, prokaryotic populations have responded successfully to many different types of environmental challenge.
- Prokaryotic populations harbor high levels of genetic diversity on which selection can act.

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

- Prokaryotic populations contain considerable genetic variation.
  - For example, a ribosomal RNA gene differs more between two strains of *E. coli* than it does between a human and a platypus.
- Three factors give rise to high levels of genetic diversity in prokaryotes: rapid reproduction, mutation, and genetic recombination.
- When a prokaryote reproduces by binary fission, some of the offspring differ slightly in genetic makeup due to mutation.
- The probability of a spontaneous mutation in a given *E. coli* gene is only about 1×10^{-7} per cell division. However, among the 2×10^{10} new *E. coli* cells that arise each day in a single human colon, approximately 2,000 will have a mutation in that gene.
  - When all 4,300 *E. coli* genes are considered, 9 million mutant *E. coli* cells arise per day per human host.
- The genetic diversity within a species like *E. coli* can lead to rapid evolution, as cells that are better equipped for the local environment survive and reproduce more successfully than others.
- Genetic recombination is another factor that generates diversity within bacterial populations.
  - Here, *recombination* is defined as the combining of DNA from two individuals into a single genome.
- Bacterial recombination occurs through three processes: transformation, transduction, and conjugation.
- **Transformation** is the alteration of a bacterial cell's genotype by the uptake of naked, foreign DNA from the surrounding environment.
  - For example, harmless *Streptococcus pneumoniae* bacteria can be transformed to pneumonia-causing cells.
  - This transformation occurs when a live nonpathogenic cell takes up a piece of DNA that happens to include the allele for pathogenicity from dead, broken-open pathogenic cells.

- The foreign allele replaces the native allele in the bacterial chromosome by genetic recombination, with an exchange of homologous DNA segments.
- The resulting cell is now recombinant, with DNA derived from two different cells.

- Years after transformation was discovered in laboratory cultures, most biologists believed that the process was too rare and haphazard to play an important role in natural bacterial populations.
- Researchers have since learned that many bacterial species have surface proteins that are specialized for the uptake of naked DNA.
- These proteins recognize and transport DNA from closely related bacterial species into the cell, which can then incorporate the foreign DNA into the genome.
- **Transduction** is a type of horizontal gene transfer that occurs when a phage carries bacterial genes from one host cell to another, as a result of aberrations in the phage reproductive cycle.
- Occasionally, a small piece of the host cell's degraded DNA, rather than the phage genome, is packaged within a phage capsid.
  - When this phage attaches to another bacterium, it injects this foreign DNA into its new host.
  - Some of this DNA can subsequently replace the homologous region of the second cell.
- Sometimes known as bacterial "sex," **conjugation** transfers genetic material between two bacterial cells that are temporarily joined.
- The transfer is one-way. One cell donates DNA, and its "mate" receives the genes.
- A hollow sex pilus from the donor initially joins the two cells and retracts to pull the two cells together.
  - A temporary *mating bridge* forms between the cells.
- The ability to form a sex pilus and donate DNA during conjugation results from an **F factor** (F for *f*ertility) as a section of the bacterial chromosome or as a plasmid.
  - The F factor consists of about 25 genes, most required for the production of sex pili.
- A cell containing the **F plasmid** is designated an F^+ cell and functions as a DNA donor during conjugation.
  - A cell lacking the F factor, designated an F^- cell, functions as a DNA recipient.
  - Transfer of the F^+ plasmid converts an F^- cell to an F^+ cell.
- The F factor can become integrated into the bacterial chromosome.
- A cell with the F factor built into its chromosome is called an Hfr cell (Hfr for *h*igh *f*requency of *r*ecombination).
- Hfr cells function as donors during conjugation.
  - When chromosomal DNA from an Hfr cell enters an F^- cell, homologous regions of the Hfr and F^- chromosomes may align, allowing segments of their DNA to be exchanged.
  - The result is the production of a recombinant bacterium that has genes derived from two different cells.
- Although the processes of horizontal gene transfer have been studied only in bacteria, it is assumed that they are also important in archaea.
- In the 1950s, Japanese physicians began to notice that some bacterial strains had evolved antibiotic resistance.

- A mutation may reduce the ability of the pathogen's cell-surface proteins to transport a particular antibiotic into the bacterial cell.
- A mutation in a different gene may alter the intracellular target protein for an antibiotic molecule, reducing its effect.
- Some bacteria have resistance genes coding for enzymes that specifically destroy certain antibiotics, like tetracycline or ampicillin.

* The genes conferring resistance are carried by plasmids, specifically the **R plasmid** (R for *r*esistance).
* When a bacterial population is exposed to an antibiotic, individuals with the R plasmid survive and increase in the overall population.
* Because R plasmids also have genes that encode for sex pili, they can be transferred from one cell to another by conjugation.
* Some R plasmids carry as many as ten genes for resistance to ten different antibiotics.