Chapter 27 – Bacteria and Archaea

I. What Are the Bacteria and Archaea?

A. Bacteria and Archaea make up the most diverse of the kingdoms.
1. Over 5000 species have been named and described.
2. Most microbes are bacteria or archaea.

B. Bacteria and Archaea are the most abundant, ubiquitous organisms on Earth.
1. Humans have more bacterial cells living in and on them than they have cells of their own bodies.
2. One teaspoon of soil has billions of bacteria living in it.
3. A drop of seawater has more *Prochlorococcus* bacteria than a large city has people.

C. Bacteria and Archaea live almost anywhere and eat almost anything.

II. Why Do Scientists Study Bacteria and Archaea?

A. A small percentage of bacteria that inhabit the human body are pathogenic and cause disease.
1. In the late 1800s Robert Koch hypothesized that bacteria may be responsible for causing infectious disease.
   a. He tested hypothesis by studying anthrax, which infects grazing animals.
   b. Koch developed four postulates required to establish a causative link between a specific microbe and a disease:
      (1) Microbe must be present in individuals suffering from the disease and absent in healthy individuals.
      (2) Organism must be isolated, grown in pure culture away from the host.
      (3) Injection of organisms from the pure culture into a healthy animal should cause the disease symptoms to appear.
      (4) The organism must then be isolated from the diseased animal, cultured again, and shown to be identical in size, shape, and color to the original organism.
   c. Koch demonstrated that for anthrax, all four postulates were true.
   d. Koch's postulates became the basis for the germ theory of disease.
      (1) Germ theory forms the basis for modern medicine.
      (2) Germ theory states bacteria and viruses cause infectious diseases.
2. Antibiotics are molecules that kill bacteria.
   a. Since their development in the late 1920s, these drugs have been very useful in combating infectious disease.
   b. The recent evolution of drug-resistant bacterial strains has presented a new challenge in modern medicine.

B. Bioremediation: The use of bacteria and archaea to clean up human pollution
1. Most pollution is caused by organic solvents and fuels leaking into water supplies.
   a. Most of these are hydrophobic and do not dissolve in water.
   b. If ingested by organisms living in soil and water, they pass through the food chain and can be toxic to eukaryotes in moderate to high amounts.
2. Sediments where these compounds accumulate can become anoxic—devoid of oxygen.
   a. Oxygen in these sediments is used up by decomposers.
   b. Once anoxic, the rate of decomposition decreases.
3. Biologists trying to clean up pollution face some problems:
   a. The slow rate of decomposition presents a problem for biologists trying to clean up the polluted sediment.
   b. Some of the toxic compounds are resistant to decomposition.
      (1) Instead of breaking down into harmless substances, compounds remain intact and toxic to organisms that ingest them.

(2) Such compounds tend to accumulate in organisms at the top of the food chain.

4. Biologists are now trying to use bioremediation strategies that use bacteria and archaea to degrade such pollutants.
   a. Fertilization of contaminated sites encourages the growth of existing bacteria that degrade the toxic compounds.
   b. "Seeding" or adding specific bacteria to polluted sites has aided in cleanup since those bacteria use the pollutant as a food source and produce a nontoxic by-product.

C. Understanding how some bacteria thrive in extreme conditions may help advance industrial technology.
   1. Extremophiles are bacteria that live in high-salt, high- or low-temperature, or high-pressure habitats.
   2. Basic scientific curiosity seeks to understand how the enzymes of these species can function under such conditions.
   3. Practical questions of interest to industry drive the study of these organisms.
   4. Astrobiologists use extremophiles as model organisms in the search for extraterrestrial life.

D. Global Change
   1. The oxygen revolution—cyanobacteria are thought to have given Earth its oxygen atmosphere.
      a. Climatologists believe no free O_2 existed in atmosphere for 2.5 billion yrs.
         (1) No plausible source of O_2 existed at the time the planet cooled.
         (2) Little, if any, O_2 is released from heated rock.
         (3) Evidence from sediments indicated any O_2 present reacted with iron and precipitated as iron oxides, hematite (Fe_2O_2), or magnetite (Fe_3O_4).
      b. Cyanobacteria, photosynthetic bacteria, were first organisms to perform oxygenic photosynthesis (releases oxygen as a by-product).
         (1) The fossil record shows that cyanobacteria first became numerous in oceans 2.7 mya.
         (2) Photosystem I, necessary for oxygenic photosynthesis, evolved in cyanobacteria.
         (3) Presence of cyanobacteria increased O_2 concentration in oceans.
      c. Once O_2 was abundant in the oceans, cells could use it as an electron acceptor.
         (1) O_2 is extremely electronegative and is a powerful electron acceptor, allowing more energy release and more ATP production when O_2 is the final electron acceptor.
         (2) Rates of energy production and metabolism rise dramatically when O_2 is the final electron acceptor.
            (*a*) The first macroscopic algae appeared 2 billion years ago.
            (*b*) Hypothesis: Multicellularity and large size were made possible by the availability of free O_2.
   2. Nitrogen fixation
      a. Plant growth is often limited by the availability of nitrogen.
         (1) The atmosphere contains abundant N_2, but plants cannot use this form of nitrogen.
         (2) Some bacteria and archaea are the only known organisms that can "fix" or transform nitrogen into forms that are usable by other organisms.
            (*a*) Bacteria and archaea absorb N_2 from the atmosphere and reduce it to NH_3.
            (*b*) Ammonia (NH_3) can be used to build amino acids and nucleic acids.
            (*c*) When they die, the nitrogen-containing compounds they have produced are available to other organisms.
         (3) If genes for the enzymes involved in nitrogen fixation can be isolated and cloned, agricultural scientists may be able to genetically engineer corn or rice with those genes, increasing crop productivity and reducing need for industrial fertilization.
      b. Nitrates as a pollutant
         (1) At present, most farmers use synthetic fertilizers to add nitrogen to soils and increase crop yields.
         (2) Ammonia fertilizer runoff has led to worldwide pollution of aquatic ecosystems.
            (*a*) Ammonia is used by crops; also by soil-dwelling bacteria and archaea.
            (*b*) Bacteria and archaea extract electrons from NH_3 and release nitrate, NO_3^- that is very water soluble and runs off fields into aquatic ecosystems.
            (*c*) Nitrate that accumulates in groundwater can be harmful to humans.

(*d*) Nitrate that accumulates in oceans acts as a fertilizer that stimulates the growth of algae and cyanobacteria, which grow to massive numbers.
(*e*) When algae and cyanobacteria die, heterotrophic archaea and bacteria are decomposers; their numbers increase dramatically.
(*f*) This decomposition uses up all the oxygen in the water.
(*g*) Anoxic "dead zones," where no aerobic organisms can live, appear in the oceans as a result of nitrate pollution.

III. How Do Biologists Study Bacteria and Archaea?

A. Bacteria are important model organisms for all fields of biology.
   1. However, our understanding of bacteria is now advancing more rapidly than any other biological field.
   2. Understanding prokaryotic diversity is now a major field in biology.

B. Using enrichment cultures to study where and how bacteria and archaea live
   1. Enrichment cultures involve establishing a specific set of living conditions.
   2. Cells that thrive under specific conditions will increase and are isolated and studied in detail.
   3. Example: Discovering bacteria from the depths of the Earth
      a. Samples were taken from rock drillings in Virginia and Colorado.
      b. Samples were taken from 860–2800 meters, where temps reach 85°C.
      c. Scientists hypothesized that if there was anything living down there, it would have to use ferric ions as the final electron acceptor in cellular respiration.
         (1) If such an organism were present in their enrichment cultures containing ferric ions, then magnetite (a black, oxidized magnetic material) would appear in the cultures.
         (2) Magnetite did appear, and microscopy confirmed the presence of some previously unidentified thermophilic bacteria that grew only at high temps.

C. Using direct sequencing to identify species that cannot be grown in enrichment culture
   1. Direct sequencing allows biologists to name and characterize organisms that have never been seen.
   2. How is a direct sequencing experiment performed?
      a. Obtain a small sample of a habitat, and isolate the bacteria and archaeal cells from the sample.
      b. Lyse open the cells and purify the DNA.
      c. Sequence specific genes and compare to existing databases.
      d. Use comparative data to determine if any "new" species are in the sample.
   3. Direct sequencing has changed the way we think about archaea.
      a. Scientists once classified prokaryotes into four basic groups:
         (1) Extreme halophiles; salt-lovers
         (2) Sulfate-reducers that produce hydrogen sulfide as a by-product
         (3) Methanogens that produce methane as a by-product
         (4) Extreme thermophiles that grow best at high temperatures
      b. However, direct sequencing experiments demonstrated that archaeal habitats are even more diverse than originally thought.
         (1) A new lineage, Korarchaeota, was identified.
         (2) This group may be diverse enough to constitute a new kingdom.
         (3) The group was named before a single species was visualized.

D. Evaluating molecular phylogenies using data from enrichment cultures and direct sequencing studies
   1. Phylogenetic trees are diagrams that illustrate the hypothesized evolutionary relationships between several analyzed species.
   2. In the 1960s Carl Woese set out to use sequence data from rRNA to infer evolutionary relationships of a diverse group of organisms.
      a. The end product of this effort is known as the tree of life.
      b. Woese subdivided prokaryotes into two new domains; bacteria and archaea.
      c. Bacteria seem to be the first lineage to emerge, implying that archaea and eukaryotes are more closely related than they are to bacteria.
      d. Further analysis has identified several monophyletic groups within each of these domains.

IV. What themes Occur in the Diversification of Bacteria and Archaea?

A. Morphological Diversity

1. What do all bacteria and archaea have in common?
    - a. Unicellular
    - b. Lack membrane-bound organelles
    - c. Divide via binary fission
2. How are bacteria and archaea different?
    - a. They have different cell membrane and cell-wall components.
        - (1) Bacteria have peptidoglycan in their cell walls.
        - (2) Archaea have unique phospholipids containing isoprenes in their plasma membranes.
    - b. They have different systems for transcription and translation.
        - (1) Bacteria have RNA polymerases that are unique from those found in archaea or eukaryotes.
        - (2) Archaeal ribosomes are more like eukaryotic ribosomes than they are like bacterial ribosomes.
    - c. Bacterial cells have plasmids (extrachromosomal DNA) that can be transferred between individuals via conjugation.
3. How are different types of bacteria different from one another?
    - a. Bacteria come in many different sizes.
        - (1) *Mycoplasmas* are the smallest bacteria, with a cell volume of 0.03 μm^3.
        - (2) *Thiomargarita namibiensis* is the largest bacteria, with volumes up to 200,000,000 μm^3.
    - b. Bacteria come in many different shapes, including filaments, rods, spheres, chains, and spirals.
    - c. Many bacteria are motile, moving via flagella or gliding.
    - d. Bacteria have cell walls with different morphologies.
        - (1) Gram-positive bacteria have a cell wall with abundant peptidoglycan.
        - (2) Gram-negative bacteria have thin, gelatinous cell wall with peptidoglycan surrounded by a phospholipid bilayer.
        - (3) These two can be distinguished by a Gram stain that reacts with the peptidoglycan.
            - (*a*) The Gram stain colors the cell wall of Gram-positive bacteria purple.
            - (*b*) The Gram stain cannot reach the peptidoglycan in the Gram-negative cell wall, so it stains pink.

B. Metabolic diversity; where do bacteria and archaea get the energy to make ATP, and where do they get carbon to build macromolecules?

1. Varying energy sources and carbon sources allow bacteria and archaea to occupy almost any habitat on Earth.
    - a. Phototrophs use the energy in light to energize electrons to fuel cellular respiration.
    - b. Organotrophs use highly reduced organic molecules such as sugars to fuel cellular respiration or fermentation.
    - c. Lithotrophs oxidize inorganic ions such as ammonia or methane to fuel cellular respiration.
    - d. Bacteria and archaea obtain carbon through carbon dioxide or methane.
2. Cellular respiration: variation in electron donors and electron acceptors
    - a. Cellular respiration is the process by which the energy is transferred from a fuel molecule (such as sugar) via redox reactions through a series of enzymatic steps and electron carriers, ultimately to an electron acceptor while that energy is harnessed to make ATP.
    - b. The nature of the fuel molecule and the nature of the final electron acceptor vary in bacterial species.
        - (1) Sugar, starch, or fatty acids are common fuel (electron donor) molecules.
        - (2) Other electron donors used by bacteria and archaea are hydrogen molecules, hydrogen sulfide, ammonia, and methane.
        - (3) When oxygen is the final electron acceptor, water is formed as a by-product.
        - (4) Other electron acceptors: sulfate, nitrate, carbon dioxide, or ferric ions
    - c. Importance of the metabolic diversity of bacteria
        - (1) Bacteria and Archaea occupy almost all possible habitats since, collectively, they can use so many types of food sources.

(2) Crucial inorganic nutrients are recycled because of bacteria and archaea.
(*a*) Bacteria and archaea can use N, C, S, and/or P in almost any form.
(*b*) N, C, S, and P are recycled from dead organisms back into living material when bacteria or archaea use them in metabolism.

3. Fermentation
   a. Fermentation is a strategy for making ATP from reduced organic compounds without involving electron transport chains.
   b. Fermentation uses no outside electron acceptor; it often occurs as an alternative pathway when no electron acceptors are available.
   c. Fermentation is a less efficient way than respiration to make ATP.
   d. Some bacteria ferment glucose to either ethanol or lactic acid.
   e. Other bacteria use various other reduced organic compounds as fermentable substrates:
      (1) *Clostridium aceticum* can ferment nonsugars, such as ethanol, acetate, or fatty acids.
      (2) Other *Clostridium* species ferment cellulose, starch, proteins, amino acids, or purines.
      (3) When *Clostridium* ferments amino acids to the end products putrescine and cadaverine, the smell of rotting flesh is produced.
      (4) Some ferment lactic acid (from milk) to propionic acid and CO_2, which give the taste and holes to Swiss cheese.
   f. As a group, the ability to ferment a variety of different substrates further extends the habitats that bacteria and archaea can occupy.
4. Photosynthesis
   a. Phototrophs use the kinetic energy of light to raise electrons to a high energy state.
   b. Photosynthesis requires a source of electrons.
      (1) Cyanobacteria and plants—water is the electron source; O_2 is released as a by-product.
      (2) Other anaerobic bacteria use different electron donors:
         (*a*) H_2S, which releases elemental sulfur as a by-product
         (*b*) Fe^{2+} (ferrous iron), which releases ferric ion (Fe^{3+}) as a by-product
5. Some phototrophic bacteria, other than cyanobacteria, use different types of chlorophyll:
   a. Seven different bacteriochlorophylls have been identified, each with a unique absorption spectrum.
   b. Hypothesis: Photosynthetic species whose chlorophylls absorb different wavelengths of light can coexist side by side without competing for light.
   c. If so, then having different chlorophylls has been an important contributor to bacteria biodiversity.
6. Pathways for fixing carbon
   a. Cyanobacteria make their own organic building-block molecules (molecules with at least one carbon-carbon bond) by fixing CO_2 (as do plants).
   b. Some bacteria and archaea fix carbon from non-CO_2 sources:
      (1) Methanotrophs use CH_4 as their primary electron donor and carbon source.
      (2) Other bacteria utilize carbon monoxide (CO) or methanol (CH_3OH) as carbon sources.
      (3) Some bacteria fix carbon using pathways other than the Calvin cycle.
   c. Different mechanisms for fixing carbon have arisen in prokaryotes in response to the need for a carbon source in a given habitat.

V. Key Lineages of Bacteria and Archaea

A. Bacteria
1. Spirochaeles
   a. Morphological diversity
      (1) Corkscrew shape
      (2) Flagella housed in an outer sheath, causing the entire cell to lash back and forth and propelling it forward.
   b. Metabolic diversity
      (1) Most make ATP via fermentation.
      (2) One species that lives in termite gut can fix nitrogen.

c. Human and ecological impact
   (1) Syphilis is caused by a spirochete.
   (2) Lyme disease is caused by a spirochete.
   (3) Live in freshwater and marine habitats; some in anaerobic conditions

2. Chlamydiales
   a. Morphological diversity—spherical and very small
   b. Metabolic diversity
      (1) All species are endosymbionts and live in hosts.
      (2) They contain few enzymes, get all nutrients from host.
   c. Human and ecological impact
      (1) *Chlamydia trachomatis* infections cause blindness in humans.
      (2) Can also cause urogenital infections if passed via intercourse.

3. High-GC Gram positives
   a. Morphological diversity
      (1) Cell walls have a lot of peptidoglycan.
      (2) Their DNA has a high guanine and cytosine content.
      (3) Cells have rod or filament shapes.
      (4) Soil-dwelling species have branched filaments called mycelia.
   b. Metabolic diversity
      (1) Many are heterotrophs that use organic compounds and oxygen for cellular respiration.
      (2) Some are parasitic.
   c. Human and ecological impact
      (1) Many antibiotics have been isolated from *Streptomyces*.
      (2) Tuberculosis and leprosy are caused by species from this group.
      (3) One species is important for making Swiss cheese.
      (4) Species in this group live in plant roots and fix nitrogen.

4. Cyanobacteria
   a. Morphological diversity
      (1) Cells can be solitary or colonial.
      (2) Colonies can form flat sheets to balls.
   b. Metabolic diversity
      (1) All perform oxygenic photosynthesis.
      (2) Some can fix nitrogen.
   c. Human and ecological impact
      (1) Produce much of the oxygen and nitrogen that other species need.
      (2) A few species live with fungi, forming lichens.

5. Low-GC Gram positives
   a. Morphological diversity
      (1) Are Gram-positive, but have a low GC-content in their DNA
      (2) Most are rod-shaped or spherical.
      (3) Can form chains or tetrads
      (4) Can form spores
   b. Metabolic diversity
      (1) Some can fix nitrogen.
      (2) Some perform nonoxygenic photosynthesis.
      (3) Some perform fermentation to make ATP; Others perform cellular respiration using hydrogen gas.
   c. Human and ecological impact
      (1) Low-GC Gram-positive species cause anthrax, botulism, tetanus walking pneumonia, gangrene, strep throat, etc.
      (2) *Lactobacillus* is used to ferment milk to make yogurt or cheese.

6. Proteobacteria
   a. Morphological diversity
      (1) Can be rods, spheres, or spirals; some form stalks.

(2) Some are motile.
(3) Some can aggregate to form fruiting bodies.

b. Metabolic diversity
(1) Live in almost any habitat.
(2) Few to none perform oxygenic photosynthesis; some perform nonoxygenic photosynthesis.
(3) Most perform cellular respiration using a variety of electron donors and acceptors.

c. Human and ecological impact
(1) Pathogenic proteobacteria cause Legionnaire's disease, cholera, food poisoning, dysentery, ulcers, and diarrhea.
(2) Some are used to make vinegar.
(3) *Rhizobium* live in root nodules of legumes and fix nitrogen.

B. Archaea
1. Crenarchaeota
a. Morphological diversity; Cells may be shaped like rods, discs, or spheres.
b. Metabolic diversity
(1) Some species make ATP via cellular respiration with a variety of electron donors and acceptors.
(2) Some species make ATP via fermentation.

2. Euryarchaeota
a. Morphological diversity
(1) Can be spherical, rod-shaped, or disc-shaped, and can aggregate in chains or balls.
(2) Some species have flagella.

b. Metabolic diversity
(1) Many species produce methane.
(2) Some species that live in high-salt environments use retinal to capture light energy and perform photosynthesis.

c. Human and ecological impact
(1) *Ferroplamas* live in piles of waste rocks near abandoned mines and produce acids that pollute nearby streams.
(2) Methanogens live in mammal gut.