Lecture III.1. Bacteria and Archaea.

Prokaryotic and eukaryotic cells compared. Not every eukaryotic cell exhibits all features shown, e.g., animal and fungal cells lack plastids; fungal and most plant cells lack undulipodia, etc.
Prokaryotes.

- Small; mostly unicellular.
- No nucleus.
- DNA organized into

1. **Circular chromosomes.**

2. **Plasmids** – exchanged during conjugation or taken up from envt.

- No mitosis; no meiosis. Reproduce by binary fission.

- No membrane-enclosed organelles – mitochondria, chloroplasts, *etc.* But, bacteria **do** possess

  1. Cytoskeleton proteins – some with eukaryotic counterparts – so-called ESPs (Lecture II.4).

  2. Protein-encased organelles such as **carboxysomes** that increase rate of photosynthesis.

Plasmid transmission when bacterial cells divide. **Top.** Independently. **Bottom.** As part of the bacterial chromosome following integration.
Components of the *Caulobacter* Cytoskeleton. Caulobacter cells have homologs of each of the three major eukaryotic cytoskeletal systems. FtsZ is a tubulin homolog that localizes to the division plane and **regulates cell division**. MreB is an actin homolog that localizes to a dynamically contracting and expanding spiral and **regulates cell shape, polarity & chromosome segregation**. CreS (crescentin) is an intermediate filament protein that localizes to *Caulobacter*’s inner curvature and **regulates cell shape**.
Carboxysomes concentrate CO₂, thereby facilitating its uptake by RuBisCO. **Left.** Schematic representation of bacterial carbon fixation. Inorganic carbon is pumped into the cytosol as bicarbonate ion (\(\text{HCO}_3^-\)) and enters the carboxysome through small pores. The carboxysome contains carbonic anhydrase (CA), which converts bicarbonate into CO₂, and RuBisCO, which catalyzes the entry of CO₂ into the Calvin cycle, the latter via reaction with ribulose-1,5-bisphosphate (RuBP). CO₂ concentration within the carboxysome is elevated by relative impermiability of the protein coat to CO₂. **Right.** Schematic showing polyhedral structure of the protein coat. Colors correspond to different sheet paralogous proteins (products of gene duplication) and interior enzymes RuBisCO and CA. The relationship of the protein coat to the coats of some viruses remains uncertain. From Samborska and Kimber (2012).
The entry of \( \text{CO}_2 \) into the Calvin cycle is catalyzed by the enzyme RuBisCO. As the cycle turns, extra G3P molecules (bottom) are produced. These three carbon sugars are subsequently converted into glucose (6 carbon sugar), which plants store as starch.
Two Prokaryote Domains: Archaea and Bacteria.

- Based on gene sequence of **small ribosomal subunit**.

1. Large and small subunits collaborate to assemble proteins (translation).

2. Highly **conserved**.

3. Three Domain theory requires that observations consistent with symbiogenic origin of Eukarya **the result of lateral gene transfer**.
Characters Shared by All Three Domains.

• **Genetic**

  1. DNA the hereditary molecule.

  2. Semi-conservative replication – daughter molecules consist of one new strand; one old.

  3. Transcription and translation: DNA $\rightarrow$ RNA $\rightarrow$ proteins.


• **Metabolic**

  1. Use of high-energy compounds such as ATP.

  2. Production of ATP by glycolysis – anaerobic respiration.

• **Structural**

  1. Ribosomes

  2. Plasma membranes and flagella – but see below.
Table I. The Three Domains Compared.

<table>
<thead>
<tr>
<th>Character</th>
<th>Bacteria</th>
<th>Archaea</th>
<th>Eukarya</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Archaea Similar to Bacteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multicellular</td>
<td>Rarely</td>
<td>No</td>
<td>Many</td>
</tr>
<tr>
<td>Nuclear Membrane</td>
<td>No</td>
<td>Rarely</td>
<td>Yes</td>
</tr>
<tr>
<td>Circular Chromosome</td>
<td>Most</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Membrane–enclosed organelles</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sex</td>
<td>No</td>
<td>???</td>
<td>Common</td>
</tr>
<tr>
<td><strong>Archaea Similar to Eukarya</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Histones associated with DNA</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Initiator tRNA</td>
<td>FMet(^1)</td>
<td>Methionine</td>
<td>Methionine</td>
</tr>
<tr>
<td><strong>Archaea Unique</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Membrane</td>
<td>See accompanying figure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Wall</td>
<td>Most include peptidoglycan</td>
<td>No peptidoglycan</td>
<td>Cellulose or chitin</td>
</tr>
<tr>
<td>Flagella</td>
<td>Grow from tip</td>
<td>Grow from base</td>
<td>Entirely different</td>
</tr>
</tbody>
</table>
Archaea Present a Mix of Characters.

- **Similar to Bacteria:**
  1. Unicellular.
  2. No nuclear envelope
  3. Circular chromosome
  4. Absence of organelles

- **Similar to Eukarya:**
  1. Histones associated with DNA.
  2. Translation initiated by methionine (Met).

- **Unique:**
  1. Plasma membrane structure.
  3. Flagellar structure and development – grow from base (archaea) vs. tip (bacteria).
Archaeal DNA is wrapped around histone tetramers. Shown here are electron micrographs taken of archaeal DNA in the presence of increasing concentrations of archaeal histone. From Marc et al. (2002).
Top. Principal component of cell membranes are phospholipids. Archaea phospholipids are composed of branched isoprene chains bound to phosphate group by ether linkages. Bacterial and eukaryote phospholipids consist of straight chain fatty acids bonded by ester linkages. In both cases, the membrane is a bilayer with the hydrophobic ends (gray) of the molecules on the inside. Bottom. Ester and Ether-linked phospholipids compared.
Prokaryotes are Important.

- **Abundant** and **ubiquitous**. Each of us has $10^{12}$ bacteria on our skin; $10^{14}$ bacteria and archaea in our digestive tract.

- Essential to proper **digestion**.

- Some bacteria **pathogenic**.

- Participate in important **geochemical cycles**, *e.g.*, **nitrogen cycle**.

1. **Nitrification.** Nitrogen fixing bacteria convert atmospheric nitrogen, $N_2$, into compounds that can be used by terrestrial plants.

2. **Denitrification.** Other prokaryotes recycle ammonia (product of decay) back to $N_2$.

- Some prokaryotes are **extremophiles**. Live in extreme environments – high temperature, acidity, salinity – that may be similar to those in which life evolved.
Prokaryotes and polysaccharide digestion. **Top.** In man; **Bottom.** In ruminants.
The nitrogen cycle. Nitrogen fixing bacteria convert atmospheric nitrogen (nitrogen fixation) to compounds that can be used by plants. Ammonia (product of decomposition) is nitrified (oxidized) to $\text{NO}_2^-$ and $\text{NO}_3^-$, which is then denitrified (reduced) to $\text{N}_2$. 
Methanogens (Archaea) are a source of methane in cows and people.
Biofilms.

- Many prokaryotes secrete a gel-like extracellular polymeric substance (EPS).

  1. Traps other bacteria.

  2. Protects against harmful environmental factors – both physical and biotic.

- Resulting mixture of cells and secretions called a biofilm.

- Examples: stromatolites; dental plaque.
Prokaryotes are Metabolically Diverse. This, plus their abundance, accounts for their important roles

- In geochemical cycles.

- In industrial applications.

- As environmental decontaminants – BP oil spill – example of ecological homeostasis.
Carbon and Energy are Universal Requirements.

- **Carbon source – two possibilities.**
  
  1. **Autotrophs** synthesize biomolecules from simple compounds such as CO₂.
  
  2. **Heterotrophs** utilize biomolecules produced by other organisms.

- **Energy source – three possibilities.**
  
  1. **Light.**
  
  2. **Organic molecules.**
  
  3. **Inorganic molecules.**
Oxidation and Reduction.

- **Oxidation** is the **loss** of electrons; **reduction**, the **acquisition** of electrons

1. **Mnemonic**: “OIL” vs. “RIG”

2. **Oxidants**
   a. Oxidize molecules from which they **remove** electrons.
   b. Are electron **acceptors**, *i.e.*, gain electrons).

3. **Reductants**
   a. Reduce other molecules to which they **donate** electrons.
   b. Are electron **donors**, *i.e.*, lose electrons).

- Cellular respiration (glycolysis, TCA cycle) entails
  1. The **oxidation** of compounds such as glucose.
  2. The **reduction** of oxidized forms of high energy compounds such as NAD$^+$, ADP, *etc.*, to NADH, ATP, *etc.*
Review of cellular respiration. In **anaerobic** metabolism, glycolysis produces high energy compounds (ATP and NADH) and pyruvate, which is converted to lactic acid (vertebrate muscle) or ethanol (yeast). **In aerobic metabolism**, pyruvate enters the TCA cycle (here called the citric acid cycle), which results in the production of additional high energy compounds (ATP, GTP, NADH and FADH$_2$). In both cases, high energy compounds other than ATP enter the electron transport chain where they are converted to ATP.
• The “light” reactions of oxygenic photosynthesis entail

1. **Reduction** of $NADP^+$ to $NADPH$ and $ADP$ to $ATP$ (sources of energy).

2. **Oxidation** of $H_2O$ to $O_2$ (source of atmospheric oxygen).

• The “dark reactions” of oxygenic photosynthesis entail

1. Oxidation of $NADPH$ to $NADP^+$ and $ATP$ to $ADP$.

2. Reduction of $CO_2$ to glyceraldehyde 3-phosphate (G3P) → sugar.

**Photosynthesis in Cyanobacteria and Plants**

In oxygenic photosynthesis, so-called “light reactions” produce high energy compounds (ATP and NADPH) and oxygen. ATP and NADH are used by so-called “dark reactions” (Calvin cycle) to convert carbon dioxide (via additional reactions) to carbohydrate.
Important Distinctions.

- **Oxygenic vs. Anoxic photosynthesis.**

  1. **Oxygenic:** the electron donor (reductant) is $H_2O$, which is oxidized to $O_2$.

  2. **Anoxic:** electron donor is something else, for example, $H_2S$, which is oxidized to elemental sulfur.

  3. In both cases, the **carbon source is $CO_2$.**

- **Anaerobic vs. Aerobic Metabolism.**

  1. In **both** cases, glucose converted to pyruvate. ATP yield is **2** molecules ATP per molecule of glucose.

  2. In **anaerobic** metabolism, pyruvate oxidized to lactic acid (vertebrate muscle) or ethanol (yeast).

  3. In **aerobic** metabolism,
     a. Pyruvate oxidized to acetyl-CoA, which enters the TCA (Krebs / citric acid) cycle.
     b. Additional ATP produced via electron transport chain. Total ATP yield is **36**.
Additional Facts Regarding Metabolism.

- **TCA Cycle Reactions.** In prokaryotes *cellular*; in eukaryotes, *mitochondrial*.

- **Glycolytic Reactions.** Cellular in both.

- **Autotrophs.**
  1. In eukaryotes, carbon source is \( CO_2 \), which is fixed via Calvin cycle (*oxygenic photosynthesis*).
  2. In prokaryotes, there are multiple carbon sources: \( CO_2 \) (cyanobacteria and others), \( CH_4 \) (methanotrophs), \( CO \), \( CH_3 OH \), *etc*.

- **Heterotrophs.**
  1. In eukaryotes, principal energy source is glucose.
  2. In prokaryotes, diverse energy sources – include glucose, ethanol, acetate, fatty acids, complex carbohydrates, proteins, amino acids, purines – *i.e.*, *just about anything imaginable*. 
Phylogenetic relations of principal groups of Bacteria and Archaea and their relation to Eukarya according to the Three Domain Scheme.
Bacteria.

- Bacterial Cell Walls.
  1. Many antibiotics target the bacterial cell wall and / or proteins involved in its synthesis.
  2. Bacterial cell walls differ with regard to thickness and placement of peptidoglycan – dense polymer of sugars and amino acids.
  3. **Gram positive** bacteria have more peptidoglycan;
  4. **Gram negative** bacteria, less.
  5. Historical basis for classifying.
  6. **But** “gram positive eubacteria” (Firmicutes, Actinobacteria, ...) includes species with gram negative walls.

Cell wall structure of gram positive and gram negative bacteria compared. Note the differences in thickness and position of the peptidoglycan layer.
• **Proteobacteria** – Purple Bacteria.

1. Metabolically diverse.

2. Primitively **photoautotrophic**.

3. Some **fix nitrogen** in legume root nodules.

4. **Myxobacteria** engage in
   
   a. Cooperative “**hunting**” via chemically mediated aggregation and synthesis of extra-cellular digestive enzymes.

   b. Formation of **multicellular “fruiting bodies”** (reproductive structures) that produce myxospores when resources scarce.

5. Proteobacteria include the **ancestors of mitochondria**.

   Phylogeny of purple bacteria showing independent acquisition of non-photoautotrophic metabolisms.
6. Some Proteobacteria are pathogenic – *e.g.*, *Helicobacter pylori*.

   a. Can cause gastritis, ulcers and cancer.

   b. Survives in stomach by creating ~**pH neutral micro-environment** in the mucosa via urease-mediated conversion of urea to CO$_2$ & NH$_3$ – itself toxic.

   c. Induces **inflammatory response** directly and via recruitment of white blood cells that produce so-called **reactive oxygen species**.
• **Cynaobacteria**
  1. **Photoautotrophs.**
  2. **Chloroplast ancestors.**
  3. Some **multicellular.**
  4. Preceded / caused **GOE.**
  5. Many fix nitrogen.

• **Spirochaetes.**
  1. Gram-negative.
  2. Axial filaments produce corkscrew-like motion.
  3. Some pathogenic: Cause **syphilis, Lyme** disease.

• **Chlamydias.**
  1. Extremely small: 0.2-1.5 \( \mu \text{m} \). Gram-negative cocci.
  2. Pathogenic – **STDs**, eye infections, some forms pneumonia.

Top. Filamentous cyanobacteria. **Bottom.** A spirochete.
• **Firmicutes.**

1. Probably not a monophyletic group.

2. *Bacillus, Clostridium, Staphylococcus.*

3. Produce long-lived **endospores** – difficult to remove from environmental (*e.g.*, hospital) surfaces.

4. Recent emergence of **antibiotic-resistant strain** of *C. difficile* (causes **diarrhea**) may be consequent to inclusion of antibiotics in cattle feed.
How *C. difficile* Spreads.

George, a 68-year-old man, goes to the doctor’s office and is diagnosed with pneumonia. He is prescribed antibiotics, drugs that put him at risk for *C. difficile* infection for several months.

One Month Later

George breaks his leg and goes to a hospital. A health care worker spreads *C. difficile* to him after forgetting to wear gloves when treating a *C. difficile* infected patient in the next room.

Rehab Facility

Does not wear gloves

Two Days Later

George transfers to a rehabilitation facility for his leg and gets diarrhea. He is not tested for *C. difficile*. The health care worker doesn’t wear gloves and infects other patients.

Hospital

Wears gloves

Three Days Later

George goes back to the hospital for treatment of diarrhea and tests positive for *C. difficile*. He is started on specific antibiotics to treat it. Health care workers wear gloves and do not spread *C. difficile*. George recovers.

SOURCE: CDC, 2012
**Actinobacteria.**

1. Many filamentous.


3. Some pathogenic – *e.g.*, *Mycobacterium tuberculosis*.

4. Important source of **antibiotics** – *e.g.*, streptomycin.

**Questions**  (Require outside reading).

2. (4 pts) Where does photosynthesis take place in cyanobacteria?

3. (4 pts) What is Lyme disease? How is it transmitted?
Archaea.

• Crenarchaeota
  1. Most thermophilic and / or acidophilic.
  2. *Sulfolobus* lives in hot sulfur springs – **requires** temperatures > 131° F.

• Euryarchaeota
  1. Some are **methanogens** – produce $CH_4$ (swamp gas) from $CO_2$. Source of
     a. 80-90% of atmospheric methane.
     b. Digestive response to sucralose.
  2. Some halophiles.

A commercial drying pond. The pink colors (carotenoids) are produced by Euryarchaeota.
Miscellaneous.

- **The Bacterial Flagellum.**
  
  1. Icon of Intelligent Design.
  
  2. Related to Type III Secretory System – injects toxins into host cells.
  
  3. Materialist-Creationist disconnect comprehensible wrt [Lakatosian Research Programmes](#).

- **H₂ Bacteria a Mile Down.**
  
  1. Oxidize Fe³⁺ to Fe₃SO₄ in the presence of H₂ at high T.
  
  2. Clue to the origin of life?

- **Cellulose** – Symbiotic bacteria and protists facilitate digestion of tough vegetation / cellulose.
  
  1. Recall bovine flatulence.
  
  2. Rumen / artiodactyl success / perissodactyl decline.
Hypothetico-deductive method with core and auxiliary hypotheses distinguished according to Lakatos [170].
Questions.

4. (6 pts) Imagine yourself a bacterium in a biofilm. Your fellow bacteria are busily producing EPS from which they and you benefit. Why shouldn’t you produce less EPS than the others? After all, EPS is metabolically expensive, and the energy saved could be used to increase your rate of cell division and therefore the numbers of your descendants. Give two possible explanations.

5. (6 pts) The word “pathogenicity” refers to the damage done—by a parasite to its host. Some bacteria are highly pathogenic— they kill their hosts quickly; others, less so. Discuss factors that might select for or against increased pathogenicity.

6. (6 pts) Bacteria produce both endotoxins and exotoxins. What is the difference? Which is more likely to give you a fever? Which are produced by the Type III secretory system? (Requires outside reading).

7. (6 pts) What is “irreducible complexity”? How does it enter into the argument for Intelligent Design? How might an intelligent designer respond to the observation that part of the bacterial flagellum is homologous
to the Type III secretory system? (Requires outside reading).