Chapter 5
The Microbial World

Oceans: the cradle of life?
- Highest diversity of life, particularly archae, bacteria, and animals
- Will start discussion of life in the ocean with prokaryote microorganisms
- Prokaryotes are also believed to be the first cellular organisms on earth
- How might life on earth have started?
- From molecules to the first cell

Cells: a sense of scale
Head of a needle

[Images of bacterial cells and a head of a needle]
Simple biological molecules can form under prebiotic conditions

- Conditions on earth during first billion years
- No free oxygen, no ozone layer to absorb UV radiation
- Atmosphere = CO$_2$, CH$_4$, NH$_3$, H$_2$
- Violent weather = eruptions, lightning, torrential rains

Simple organic molecules are likely to have been produced under such conditions

Laboratory “created” molecules

<table>
<thead>
<tr>
<th>HCHO</th>
<th>formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCOOH</td>
<td>formic acid</td>
</tr>
<tr>
<td>HCN</td>
<td>hydrogen cyanide</td>
</tr>
<tr>
<td>CH$_3$COOH</td>
<td>acetic acid</td>
</tr>
<tr>
<td>NH$_2$CH$_2$COOH</td>
<td>glycine</td>
</tr>
<tr>
<td>CH$_3$CHCOOH</td>
<td>lactic acid</td>
</tr>
<tr>
<td>NH$_2$CH$_2$COOH</td>
<td>alanine</td>
</tr>
<tr>
<td>NH—CH$_2$COOH</td>
<td>serine</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>ammonia</td>
</tr>
<tr>
<td>NH$_2$CH$_2$</td>
<td>urea</td>
</tr>
<tr>
<td>NH$_2$CH$_2$COOH</td>
<td>aspartic acid</td>
</tr>
</tbody>
</table>

Formation of polymers from simple organic compounds

- Amino acids (aa) can join by forming peptide bonds
- Nucleotides (nt) can join by forming phosphodiester bonds
- In present day cells - polypeptides (proteins) are from aa, polynucleotides (RNA and DNA) are from nt.

Sugars such as ribose
Spontaneous polymerization of random polymers

Earliest polymers were of variable length and random sequence
- Mechanism of formation
  - Heating of dry organic compounds
  - Catalytic activity of inorganic polyphosphates or other mineral catalysts
- Polymers can influence subsequent reactions by acting as a catalyst

Autocatalytic systems
- Origin of life requires that some polymers must have a crucial property: the ability to catalyze reactions that lead to the production of more molecules of itself.
- This can be accomplished by polynucleotides

Complementary templating

Ribozymes
- Catalytic RNA molecule
- Believed to be the basis for the first autocatalytic systems
- Acts as both template and catalyst
- Eventually specialization where DNA is the template and proteins are catalysts
Self-replicating RNA systems
• Start with a catalytic RNA molecule that polymerizes nucleotides to reproduce itself

The beginning of evolution
• 3.5 to 4 billion years ago - mixture of self-replicating RNA systems and organic molecule precursors
• Systems with different sets of polymers competed for the available precursors
• Success depended on the accuracy and speed with which the copies were made and the stability of these copies

From polynucleotides to peptides
• Polynucleotides are well suited for information and storage but have limited catalytic properties
• Proteins have much greater catalytic capabilities
• In modern cells, synthesis of proteins is catalyzed by ribosomes (proteins and RNA) from RNA templates.

Primative RNA/protein systems
• Would have an advantage over RNA only systems due to better catalysis facilitated by proteins
Membranes defined the first cell

- An illustration of a protocell, composed of a fatty acid membrane encapsulating RNA ribozymes.

The need for containment is filled by amphipathic molecules

- Amphipathic - property where one part of the molecule is hydrophobic and the other part is hydrophilic.
- In present-day cells, these amphipathic molecules are primarily phospholipids.

Membranes defined the first cell

- The development of an outer membrane was a crucial event
- Proteins synthesized by a certain species of RNA would not increase reproduction of that RNA species unless they remained in the neighborhood of the RNA
- Proteins could diffuse away and benefit competing RNA molecules

Membranes are readily formed from amphipathic molecules

- Example: phospholipids
  - Hydrophobic tail group
  - Hydrophilic head group
- Mix in water and membranes spontaneously form
• A simple fatty acid (far left) may have been a major component of early cell membranes. To the right of the fatty acid is a phospholipid, which is the primary component of modern cell membranes. Vesicles and micelles, shown on the right, are structures that can be formed by fatty acids or phospholipids. Mouse-over the vesicle or micelle to see the whole structure.

Summary of the hypothetical evolution of the first cells

RNA-based systems

DNA-based systems have advantages over RNA-based systems

All present-day cells use DNA as their hereditary material

From self-replicating RNA to present day cells

• DNA acts as a permanent repository of genetic information
  – Is found principally in a double-stranded form which is more robust and stable
  – If there is breakage, there is a repair mechanism that uses the intact strand as a template.
• DNA templates can become more complex

• RNA preceded DNA and proteins, having both catalytic and genetic properties.
• Proteins eventually became the major catalysts
• DNA became the primary genetic material
• RNA continues to function in coding for proteins (mRNA) and catalysis (rRNA).
From procaryotes to eucaryotes

- 1.5 billion years ago there was a transition from relatively simple procaryotic cells to larger more complex eucaryotic cells.

The earliest procaryotes were like present day bacteria

- Bacteria
  - Simplest organisms
  - Spherical or rod shaped several microns long
  - Tough protective coat (cell wall)
  - Plasma membrane enclosing a single cytoplasmic compartment
  - DNA, RNA, proteins, and small molecules

Procaryotes generally have no obvious internal structures

Metabolic reactions evolve

- A bacterium growing in a simple solution containing glucose must carry out hundreds of different reactions.
- Glucose used for chemical energy and as a precursor for all organic molecules the cell requires.

Originally, there was little need for so many metabolic reactions

- Cells with simple chemistry could survive and grow on the molecules in their surroundings.
- Eventually these molecules would become limited and cells devised ways to manufacture what they couldn’t acquire.
- This led to metabolic complexity.

Glycolysis, the oldest metabolic pathway

- Degradation of sugar phosphates in the absence of oxygen occurs by glycolysis
- Glycolysis is similar in all kinds of organisms -- suggesting an extremely ancient origin
- Metabolism evolved by sequential addition of new enzymatic reactions to existing ones.
- In present-day organisms hundreds of chemical processes are linked to...
Cyanobacteria can fix CO$_2$ and N$_2$

- A strong selective advantage would eventually be gained by organisms able to use C and N directly from the atmosphere.
- CO$_2$ and N$_2$ are very stable and require a large amount of energy as well as complicated chemical reactions to convert them to organic molecules

Photosynthesis and nitrogen fixation

- Process that used energy from sunlight to convert CO$_2$ and N$_2$ into organic compounds.
- Cyanobacteria (blue-green) algae are the most self-sufficient organisms that now exist.
- The metabolic activity of these organisms set the stage for the evolution of more complex organisms

Atmospheric oxygen and the course of evolution

Aerobic respiration

- Accumulation of oxygen in the atmosphere led to the ability to oxidize more completely ingested molecules
- Also oxygen was toxic to many early anaerobic organisms
- By around 1.5 billion years ago, organisms with aerobic respiration became widespread

Origin of eucaryotic cells with distinct organelles

- What happened to the anaerobic organisms?
  - Many found low oxygen niches
- Some acquired aerobic cells as intracellular symbionts giving rise to eucaryotes

Features of eucaryotic cells

- Have a nucleus containing most of the cell’s DNA
Features of eucaryotic cells

• Outside the nucleus is the cytoplasm where most of the cell’s metabolic reactions occur.
• The cytoplasm contains distinctive organelles
  – Prominent organelles are chloroplasts and mitochondria
  – Each is enclosed in its own membrane

Mitochondria

• Similar to free-living prokaryotic cells
• Resemble bacteria in size and shape
• Contain DNA, make protein, and reproduce by dividing in two
• Without mitochondria eukaryotic cells would be anaerobic organisms
• By engulfing mitochondria, internal oxygen concentrations are kept low

Eucaryotic cells depend on mitochondria for aerobic respiration

• Mitochondria are found in virtually all eukaryotic cells including plants and animals

Acquisition of mitochondria may have allowed evolution of new features

• Plasma membrane of mitochondria and procaryotes is heavily committed to energy metabolism
• In contrast eucaryote membrane is not.
• Eucaryote membrane developed new features
  – Example: ion channels allowing electrical signaling

Some present day organisms may resemble the hypothetical ancestral eucaryote precursor

• They have nuclei but lack mitochondria
• Example the diplomonad Giardia
Giardia
• Live as parasites in the guts of animals (including humans)
  – Low oxygen environment
  – Rich in nutrients allowing them to survive on inefficient anaerobic metabolism

Chloroplasts are descendants of an engulfed procaryotic cell
• Similarities to cyanobacteria
  – Carry out photosynthesis
  – Structural resemblance (size, stacked membranes)
  – Reproduce by dividing
  – Contain DNA nearly indistinguishable from portions of a bacterial chromosome

Some present-day cells contain authentic cyanobacteria
• Cyanophora paradoxa

The postulated origin of present-day eucaryotes