Lecture Series 14
Origins of Life, Early Earth
& Prokaryotic Diversity
The Chemical Aspects of The Origin of Life

Life is the cumulative product of interactions among the many kinds of chemical substances that make up the cells of an organism.

The abiotic chemical evolution of life follows four major hurdles:

1. The abiotic synthesis and accumulation of small organic molecules, or monomers, such as amino acids and nucleotides.
2. The joining of these monomers into polymers, including proteins and nucleic acids.
3. The aggregation of abiotically produced molecules into droplets, e.g., protobionts, that had chemical characteristics different from their surroundings.
4. The origin of heredity or information transference.
To understand how the origin of life from abiotic material occurred, we have to consider two critical concepts:

1. The extension of the idea of natural selection to the chemical level.

2. The realization that the condition of the early Earth when life first arose must have been vastly different from present:

   (a) Non-oxidizing atmosphere: present level of oxygen, which began to accumulate around 2.1 billion years ago with the presence of cyanobacteria, would have been lethal to primitive organisms

   (b) Abundant resources produced non-biologically

   (c) Long time scale without competition
The Molecular Clues to the Origin of Life on Earth

- Molecules of living organisms are rich in hydrogen-containing carbon compounds that are highly reduced. This suggests that there were little or no free molecular oxygen on primitive Earth.

- All amino acids exist in both the right-handed and left-handed state. However, only 20 amino acids of the left-handed variety are used by living organisms in proteins. Therefore, suggesting there was a single origin of life.

- DNA & RNA are the universal informational basis of all life forms on Earth.

- ATP is the universal energy currency of all living organisms; suggesting a common origin of metabolism.

- In any cell, first steps of carbohydrate metabolism involve fermentation, with the last steps in aerobic organisms the usage of oxygen via respiration – suggesting that aerobic organisms evolved from anaerobic ones.
Necessary Conditions for the Origin of Life

- Earth at the time of life’s origin had a reducing atmosphere. Under conditions that resemble Earth’s early atmosphere, small molecules essential to living systems form and polymerize.
Diagram of Stanley Miller’s apparatus

**EXPERIMENT**

**Question:** Can organic compounds be generated under conditions similar to those that existed on primeval Earth?

**METHOD**

- **“Oceanic” compartment**
- **“Atmospheric” compartment**
- **Condensation**
- **Heat**
- **Cold water**
- **N₂, CH₄, NH₃, H₂, CO₂, H₂O**

**RESULTS**

**Conclusion:** The organic building blocks of life are generated in the probable atmosphere of early Earth.
Necessary Conditions for the Origin of Life

• Before life appeared, polymerization reactions generated the carbohydrates, lipids, amino acids, and nucleic acids of which organisms are composed. These molecules accumulated in the oceans.

• Originally “Darwin’s Warm Pond” Hypothesis
A painting of early Earth showing volcanic activity and photosynthetic prokaryotes in dense mats
Protobionts: Enclosing Prebiotic Systems

- The earliest protobionts probably had lipid-based membranes.
Laboratory versions of protobionts

Putative “Metabolism” of a Coacervate Drop
Protobionts: Enclosing Prebiotic Systems

- The first genetic material may have been RNA that had a catalytic function and an information transfer function. Some RNA’s—called ribozymes—have catalytic functions today.
A Ribozyme from a Protist

Folding brings together complementary but distant base sequences allowing catalytic activity to occur.
**Figure 1** Peptide bond formation by a ribosome (left) and by a ribozyme (right).
Protobionts: Enclosing Prebiotic Systems

- DNA probably evolved after RNA-based life became surrounded by membranes that provided an environment in which DNA was stable.
Abiotic replication of RNA

RNA monomers → Formation of short RNA polymers → Assembly of a complementary RNA chain (pairing rules are G with C and A with U) → Complementary chain serves as template for making copy of original “gene”
The RNA World

Sterile Earth

- Prebiotic syntheses (proteins and RNA made abiotically)
- RNA
- Self-replicating RNAs
  - Lipoprotein vesicle
  - Early cellular life (RNA as coding and catalytic molecule)

- Evolution of DNA from RNA
  - DNA

- Proteins assume catalytic functions (RNA only as coding molecule)
  - Protein

- Modern cellular life (DNA replaces RNA as coding molecule leading to DNA → RNA → Protein)
Photosynthesis Is the Source of Atmospheric O$_2$

- Cyanobacteria, which evolved the ability to split water into hydrogen ions and O$_2$, created atmospheric O$_2$. Accumulation of free O$_2$ in the atmosphere made possible the evolution of aerobic metabolism.
Fossil Stromatolites and mat communities
Living columnar stromatolites, Shark Bay, Western Australia
Modern Stromatolites from Yellowstone Natl. Park
Early (left) and modern (right) prokaryotes
Microbial mat communities
Fossil Stromatolites from Glacier Natl. Park
Is Life Evolving from Nonlife Today?

- Because most of the chemical reactions that gave rise to life occur readily under the conditions that prevailed on early Earth, life’s evolution was “probably” inevitable.

- Experiments by Louis Pasteur and others convinced scientists that life does not come from nonlife on Earth today.
Pasteur was the father of “origins of life” research in addition to microbiology & cell biology.

Architect of Germ Theory.
Is Life Evolving from Nonlife Today?

- New life is no longer being assembled from nonliving matter because simple biological molecules that form in today’s environment are oxidized or consumed by existing life.

- Now we have competition & oxygen!
Volcanic activity and lightning associated with the birth of the island of Surtsey near Iceland; terrestrial life began colonizing Surtsey soon after its birth
Does Life Exist Elsewhere in the Universe?

- Conditions that permit the evolution and maintenance of simple prokaryotic life may be widespread in the universe, but multicellular life has more stringent requirements, including a planet with a relatively circular orbit, a rapid rate of spin, nearby planets that intercept impacts, and a large moon that stabilizes the planet’s orbit. Such conditions may be very rare.
Impact Frustration period forces origins of life into a narrow time period to have gotten started!

Hydrothermal vents may have served as zones of refuge.
Origin of Life???
Europa, Jupiter’s moon: Astrobiology???
Does Life Exist Elsewhere in the Universe?

- Although conditions on Earth have fluctuated greatly, they have been suitable for multicellular organisms for nearly a billion years.
Why Three Domains?

• Living organisms can be divided into three domains: Bacteria, Archaea, and Eucarya. The prokaryotic domains (Archaea and Bacteria) differ from each other more radically than the Archaea from the Eucarya.
Figure 1. Diagrammatic “Universal” phylogenetic tree of life, based on small-subunit ribosomal RNA sequences. Based on analyses of Barns et al. (1996b), Olsen et al. (1994), and Sogin (1994).
Why Three Domains?

• Evolutionary relationships of the domains were revealed by rRNA sequences. Their common ancestor lived more than 3.6 - 3.8 billion years ago, prior to that of the common ancestor of the Archaea and Eucarya.
Some Lessons from the BIG TREE: Map of the Biological Record

Single origin for all life on Earth...

- Central Dogma intact
- ATP and PMF are universal themes
- Uniformity among chiral carbon compds (sugars & AAs)
- Hot start origin...

- Also Cyanobacteria did not arrive first on the scene!
- Now estimated at 2.5 –2.1 bya
Some Lessons from the BIG TREE:
Map of the Biological Record

General topology implies:

- Three “primary lines of evolutionary descent.”
- The Eucarya “nuclear” lineage almost as old as the prokaryote lines.
- Prokaryotes split between *Bacteria* and *Archaea*.
- Shown for only a limited number of representative org’s.
- Mitochondria and chloroplasts proven to be of bacterial origin.
### Table 27.2 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 start of protein synthesis</td>
<td>Formyl-methionine</td>
<td>Methionine</td>
<td>Methionine</td>
</tr>
<tr>
<td>Introns (noncoding parts of genes)</td>
<td>Absent</td>
<td>Present in some genes</td>
<td>Present</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</td>
<td>Present</td>
</tr>
<tr>
<td>Circular chromosome</td>
<td>Present</td>
<td>Present</td>
<td>Absent</td>
</tr>
<tr>
<td>Ability to grow at temperatures &gt;100°C</td>
<td>No</td>
<td>Some species</td>
<td>No</td>
</tr>
</tbody>
</table>
Evolution of the main lines of descent
Evolution of the main lines of descent

- **Alga with chloroplast**
- **Eukarya with mitochondrion**

4. Symbiosis leads to chloroplast.

Plants

3. Symbiosis leads to mitochondrion.

Some protists

Animals
Whittaker’s five-kingdom system

- **Plantae**
- **Fungi**
- **Animalia**

- **Protista**
- **Monera**

**Eukaryotes**

**Prokaryotes**
Our changing view of biological diversity

(a) The five-kingdom system

(b) The three-domain system

(c) How many kingdoms?
General Biology of the Prokaryotes

- The prokaryotes are the most numerous organisms on Earth, occupying an enormous variety of habitats.

- Most prokaryotes are cocci, bacilli, or spiral forms. Some link together to form associations, but very few are truly multicellular.
“Heat-loving” prokaryotes
Hot springs, home of thermophiles
Extreme halophiles
The most common shapes of prokaryotes
General Biology of the Prokaryotes

- Prokaryotes lack nuclei, membrane-enclosed organelles, and cytoskeletons. Their chromosomes are circular. They often contain plasmids. Some contain internal membrane systems.

- Prokaryotes reproduce asexually by binary fission, but also exchange genetic information.
Specialized membranes of prokaryotes
General Biology of the Prokaryotes

- Prokaryotes’ metabolic pathways and nutritional modes include obligate and facultative anaerobes, and obligate aerobes. Nutritional types include photoautotrophs, photoheterotrophs, chemoaototrophs, and chemoheterotrophs. Some base energy metabolism on nitrogen- or sulfur-containing ions.
## Table 27.1 Major Nutritional Modes

<table>
<thead>
<tr>
<th>Mode of Nutrition</th>
<th>Energy Source</th>
<th>Carbon Source</th>
<th>Types of Organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autotroph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo-autotroph</td>
<td>Light</td>
<td>CO₂</td>
<td>Photosynthetic prokaryotes, including cyanobacteria; plants; certain protists (algae)</td>
</tr>
<tr>
<td>Chemo-autotroph</td>
<td>Inorganic chemicals</td>
<td>CO₂</td>
<td>Certain prokaryotes (for example, <em>Sulfolobus</em>)</td>
</tr>
<tr>
<td>Heterotroph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo-heterotroph</td>
<td>Light</td>
<td>Organic compounds</td>
<td>Certain prokaryotes</td>
</tr>
<tr>
<td>Chemo-heterotroph</td>
<td>Organic compounds</td>
<td>Organic compounds</td>
<td>Many prokaryotes and protists; fungi; animals; some parasitic plants</td>
</tr>
</tbody>
</table>
Model for the development of **Porphyrin Ring** diversity regarding metabolic pathways
Action Spectra

Relative absorption

Purple sulfur bacteria

Uvva sp.

Wavelength (nm)

300 400 500 600 700 800 900 1000
Contrasting hypotheses for the taxonomic distribution of photosynthesis among prokaryotes

Hypothesis (a): Photosynthesis evolved many times.

Hypothesis (b): Photosynthesis evolved once.
One of the most independent organisms on earth: Cyanobacteria (*Anabaena*)
Beggiatoa, sulfur-eating bacteria
The largest known prokaryote
Some major episodes in the history of life:

- Origin of Earth
- Earth cool enough for crust to solidify
- Origin of life
- Oldest chemical evidence of life
- Oldest prokaryotic fossils
- Oxygen produced by cyanobacteria begins to appear in atmosphere
- Oldest eukaryotic fossils
- Origin of multicellular eukaryotes
- Plants and symbiotic fungi colonize land
- Oldest animal fossils
- Extinction of dinosaurs
- First humans

- Prokaryotes
  - Bacteria
  - Archaea
- "Protists"
- Eukaryotes
  - Plants
  - Fungi
  - Animals

- Cenozoic
- Mesozoic
- Paleozoic

Millions of years ago:
Formation of the earth

(~ 4.6 X 10^9 years before the present)

Prebiotic synthesis of biomolecules

Chemical evolution

Origin of life

Archaea

Bacteria

First phototrophic bacteria

Nuclear line

Origin of oxygenic phototrophs (cyanobacteria)

Traces of earliest eukaryotes

Oxygenated environment

Endosymbiosis

Origin of modern eukaryotes

Origin of metazoans

“Higher” organisms

“Higher” organisms

Morphological evolution of metazoans

Cambrian

Precambrian (>500 million years ago)

O_2 (percent in atmosphere)

Anoxic

Oxic
Evolutionary clock: Origin of life
Evolutionary clock: Prokaryotes
Evolutionary clock: Animals
Evolutionary clock: Land plants

Land plants

Billions of years ago

1 2 3 4
Clock analogy for some key events in evolutionary history
Figure 2.7 Cumulative history of $O_2$ released by photosynthesis through geologic time. Of more than $5.1 \times 10^{22} \text{ g}$ of $O_2$ released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although $O_2$ was released to the atmosphere beginning about 2.0 bya, it was consumed in terrestrial weathering processes to form Red Beds, so that the accumulation of $O_2$ to present levels in the atmosphere was delayed to 400 mya. Modified from Schidlowski (1980).
Banded iron formations are evidence of the vintage of oxygenic photosynthesis
Patterns of Evolutionary Change

• The Oxygen "Blip" @ ~300 mya resulted from the invasion of land by plants!

• This gave rise to:
  • Gigantic Insects
  • Origin of Flight
  • Invasion of land by animals
Patterns of Evolutionary Change

- Truly novel features of organisms have evolved infrequently. Most evolutionary changes are the result of modifications of already existing structures.
Fossilized animal embryos from Chinese sediments 570 million years old
The Cambrian radiation of animals
18s rDNA sequence phylogeny

MARINIOAN GLACIATION

SQUNTUM GLACIATION

Faunal diversity

Arthropoda
Nematoda
Priapula
Mollusca
Annelida
Platyhelminthes
Brachiopoda
Chordata
Echinodermata
Cnidaria
Porifera

orders
classes

LATE NEOPROTEROZOIC
CAMBRIAN

AGE (millions of years before present)

600
550
500

THE METAZOAN EXPLOSION

1 Ecdysozoa
2 Lophotrochozoa
3 Deuterostoma
Patterns of Evolutionary Change

• Over evolutionary time, organisms have increased in size and complexity. Predation rates have also increased, resulting in the evolution of better defenses among prey species.
The Future of Evolution

• The agents of evolution continue to operate today, but human intervention, both deliberate and inadvertent, now plays an unprecedented role in the history of life.

• Global Warming

• The Human Bolide