Origin and Evolution of Life on Earth – Chapter 6 Overview

• Searching for the origin (6.1)
• Functional beginnings of life (6.2)
  – From chemistry to biology at the molecular level
• Prokaryotes and oxygen (6.3)
• Eukaryotes and explosion of diversity (6.3)
• Mass extinctions, asteroids and climate change (6.4)
• Evolutions of humans (6.5)
• Science in Action: Artificial Life (6.6)
Searching for the origin

• **Origin of Life Theories**
  - **Special Creation**
    • Oldest and most widely accepted hypothesis.
  - **Extraterrestrial Origin**
    • Panspermia - Cosmic material may have carried complex organic molecules to earth.
  - **Spontaneous Origin**
    • Life evolved from inanimate matter.
Panspermia
Science Searching for the Origin

• Tools and methodologies
  - Principles of physics (e.g., 1st and 2nd Law of TD)
  - Principles of geology (e.g., relative/absolute dating)
  - Principles of chemistry (e.g., chemistry of water)
  - Principles of biology (e.g., key macromolecules)
  - Occam’s razor where appropriate

• Conclusions: plausible scenario of the events and processes that lead to the origin of life
Searching for the Origin: Where on Earth?

• **Options**
  - Continental landscapes
  - Shallow pools
  - Hot springs
  - Deep sea vents
  - Deep in crust
  - Under frozen seas

• **Data to support one or the other**
  - Comparative genomics
  - Chemical energy (hydrogen sulfide)
    \[ \text{FeS} + \text{H}_2\text{S} \rightarrow \text{FeS}_2 + \text{H}_2 + \text{Free Energy} \]

• **Conclusion: deep sea vents**
  - Probability of bombardment
Searching for the Origin

- When did life begin?
- Evidence
  - Widespread life forms (3.5 B years ago)
  - Stromatolites (3.5 B years ago)
  - Fossilized cells (3.5 B years ago)
  - Radiometric dating: carbon isotopes (3.85 B years ago)
    - Carbon 12 versus Carbon 13
- Range of dates: 4.1 to 3.85 B years ago
- Conclusions
  - Life arose late in the Hadean Eon
  - Life colonized planet in very short time frame (< 500 M years)
Searching for the Origin: Comparative Genomics

- Comparative morphology versus comparative genomics
- “Living Fossils” of DNA and RNA
  - Sequence of nucleotides in DNA and genome
  - Pattern and process of change in sequences
  - Comparing sequences reveals a pattern/order
- Methodology of comparison - rRNA (ribosomal RNA)
Searching for the Origin: Three Branches of Life Forms

• Results from comparative genomics
  - Three major domains
    • Bacteria
    • Archaea
    • Eukarya

• Common ancestor analysis

• Comparison to organisms today
  - Deep sea volcanic vents
  - Thermophiles (hyperthermophiles)
  - Comparison to environment of Hadean Eon
Searching for the Origin

Domain Bacteria
Domain Archaea
Domain Eukarya

Common Ancestor
Life and Atmosphere

• One assumption about the early atmosphere was a reducing atmosphere of carbon dioxide, nitrogen gas, and water vapor, but very little oxygen.
  - Amino acids would therefore not last long.
  • Atmosphere would have changed with the advent of photosynthesis.
Beginnings of Life on Earth

- Organic chemistry*
- Transition from chemistry to biology
- Panspermia
- The evolution of sophisticated features of metabolism and information brokers
- Conclusions

* Enzymes first or TCA or ?
The Citric Acid Cycle
iClicker Question

• The origin of life on Earth most likely occurred
  - A before 4.5 billion years ago
  - B between about 4.5 billion years ago and 3.5 billion years ago
  - C between about 3.0 billion years ago and 2.5 billion years ago
  - D between about 2.5 billion years ago and 2.0 billion years ago
The first living organisms probably were
- A cells without nuclei that used RNA as their genetic material
- B cells with nuclei that used RNA as their genetic material
- C cells with nuclei that used DNA as their genetic material
Miller-Urey Experiment

• Stanley Miller and Harold Urey (1953) attempted to reproduce conditions at the ocean’s edge under a reducing atmosphere.
  - Were able to form amino acids with the addition of lightning to a reducing atmosphere rich in hydrogen and devoid of oxygen.
Miller-Urey Experiment

- Water vapor
- Electrodes discharge sparks (lightning simulation)
- Mixture of gases ("primitive atmosphere")
- Stopcocks for testing samples
- Condensor
- Water
- Heated water ("ocean")
- Condensed liquid with complex molecules
Significance of and Sequel to Urey Miller Experiment

• Multiple variations of the study (e.g., atmosphere)
  - 20+ amino acids, sugars, bases for DNA and RNA, ATP, etc.
• Significance: scenario for the abiotic formation of key carbon polymers (macromolecules)
• Probable environments
  - Deep sea vents
  - Tidal pools (role of repeated evaporation and concentration
    - “evapoconcentration”; asteroid bombardment)
• Chemical events leading to an “RNA World”
Chemical Beginnings

Chemical Evolution on Early Earth

Earth early cools, outgassing

early hot atmosphere that cools and H₂O condenses to form oceans

warm pools rich in CO₂, H₂O, NH₃, CH₄ → primordial soup

primordial soup → energy (solar, UV, electric discharge, heat)

Miller-Urey experiment

output = organic compounds

amino acids → proteins
base purines → nucleic acids
carbohydrates → polysaccharides
fatly acids → lipids

building blocks of self-replicating molecules
iClicker Question

• The importance of the Miller-Urey experiment is that
  - A it proved beyond doubt that life could have arisen naturally on the young Earth.
  - B it showed that natural chemical reactions can produce building blocks of life.
  - C it showed that clay can catalyze the production of RNA.
Evolutionary Perspective of Enzymes

• Evolutionary advantage of enzymes
  - Specific acceleration of reactions
  - Fitness value: positive
  - Information broker: coded in the DNA
    • Mutation
    • Reproduction

• How did enzymes come to be?
Ribozymes

• **What are ribozymes** *(from ribonucleic acid enzyme)*?
  - *NOT* ribosomes *(components of cells where proteins built from amino acids)*
  - mRNA *(small fragments)*
  - Functions
    • Synthesis of RNA, membranes, amino acids, ribosomes
  - Properties
    • Catalytic behavior *(enhance rates ~20 times)*
    • Genetically programmed
    • Naturally occurring *(60-90 bases)*
Ribozymes (continued)

- Laboratory studies of ribozymes
  - Creation of RNA fragments at random with existence of enzyme-like properties
  - Variety of enzyme-like properties
    - Cleavage of DNA
    - Cleave of DNA-RNA hybrids
    - Linking together fragments of DNA
    - Linking together fragments of RNA
    - Transformation of polypeptides to proteins
    - Self-replication (2001)
Summary of Ribozymes

- mRNA fragments
- 3-D conformation like proteins (e.g., fold)
- Functional ribozymes created at random in test tube
- Exhibit catalytic behavior
- Self replicate
- Play a prominent/key role in any scenario for understanding the evolution of life at the biochemical and molecular level
RNA World
Functional Beginnings of Life: Transition from Chemistry to Biology

- Ribozymes
  - Enzyme activity
  - Self replicating

- Generation of biomacromolecules (C polymers; e.g., sugars, nucleotides, ATP)
  - *via* abiotic processes on Earth (Urey-Miller)
  - *via* Panspermia
  - *via* biotic processes (e.g., ribozymes)

- Role of mutations, natural selection and environment: incremental changes in biomacromolecules that are inherited *via* RNA and DNA)
Chemical Evolution

• Debated if RNA or Proteins evolved first.
  - RNA Group believes other complex molecules could not have been formed without a heredity molecule.
  - Protein Group argues that without enzymes, replication would not be possible.
  - Peptide-Nucleic Acid Group believes peptide nucleic acid was precursor to RNA.
Functional Beginnings of Life: Transition from Chemistry to Biology

• Evolution of Photosynthesis
  \[ CO_2 + H_2O + \text{Light} = CH_2O + O_2 \]
• Key processes
  - Absorption of light (pigments)
  - Conversion of light energy into chemical energy (ATP)
  - Synthesis of simple carbon compounds for storage of energy
• Purple bacteria and Cyanobacteria
  - Primitive forms (~3.5 BYA)
iClicker Question

• “RNA world” refers to
  - A the possibility that life migrated from Mars.
  - B the idea that RNA was life’s genetic material before DNA.
  - C the idea that early life was made exclusively from RNA, needing no other organic chemicals.
Ocean Edge Scenario

• Bubble Theory - Bubble structure shielded hydrophobic regions of molecules from contact with water.
  - Alexander Oparin - Primary abiogenesis.
• Photobionts - Chemical-concentrating bubble-like structures which allowed cells a means of developing chemical complexity.
Current Bubble Hypothesis

1. Volcanoes erupted under the sea, releasing gases enclosed in bubbles.
2. The gases, concentrated inside the bubbles, reacted to produce simple molecules.
3. When the bubbles persisted long enough to rise to the surface, they popped, releasing their contents to the air.
4. Bombarded by the sun's ultraviolet radiation, lightning, and other energy sources, the simple organic molecules released from the bubbles reacted to form more complex organic molecules.
5. The more complex organic molecules fell back into the sea in raindrops. There, they could again be enclosed in bubbles and begin the process again.
Prokaryotes

- Microfossils - Earliest evidence of life appears in fossilized forms of microscopic life.
  - Physically resemble bacteria.
    - Prokaryotes - Lack nucleus.
      - Remember Eukaryotes contain nucleus
Prokaryotes

• *Archaebacteria* - Ancient bacteria that live in extremely hostile conditions.
  - Lack peptidoglycan in cell walls.
  - Have unusual lipids in cell membranes.
    • *Methanogens* (microorganisms that produce methane as a metabolic byproduct)
      - Anaerobic
    • *Halophiles*
    • *Thermophiles*
Prokaryotes and Atmospheric Oxygen

% of Present

Billions of Years Before Present
Prokaryotes and Oxygen

• Evolution of Photosynthesis
  \[ CO_2 + H_2O + \text{Energy} = CH_2O + O_2 \]

• Evolution of respiration
  \[ CH_2O + O_2 = CO_2 + H_2O + \text{Energy} \]

• Possibility that respiration is simply the reverse of photosynthesis

• Oxygen crisis and the oxygen stimulation to evolution
iClicker Question

• The oxygen in Earth’s atmosphere was originally released by
  - A outgassing from volcanoes.
  - B plants.
  - C cyanobacteria.
iClicker Question

• Early life arose in an oxygen-free environment, and if any of these microbes had somehow come in contact with molecular oxygen, the most likely effect would have been
  - A nothing at all.
  - B to increase their metabolic rates.
  - C to kill them.
iClicker Question

• Which statement about the Earth’s ozone layer is not true?
  - A It protects us from dangerous solar radiation.
  - B It did not exist when life first arose on Earth.
  - C It first formed a few hundred million years after life colonized the land.
Eukaryotes and an Explosion of Diversity

• Incremental changes in evolution: role of oxygen and diversification of organisms (explain ATP fitness)

• Quantum changes in evolution
  - Symbiosis
  - Lynn Margulis theory: eukaryotes are derived from prokaryotes
  - Compartmentalization and organelles
  - Bacterial origins of chloroplast and mitochondria
Eukaryotes and explosion of diversity

• **Eubacteria** - Second major bacterial group.
  - Contain very strong cell walls and simpler gene architecture.

• **Cyanobacteria**
  - Photosynthetic
    » Appeared at least 3 bya
First Eukaryotic Cells

• First appeared about 1.5 bya. (maybe earlier)
  - Possess internal nucleus.
• Endoplasmic Reticulum - Network of internal membranes in eukaryotes.
  - Both Endoplasmic Reticulum and nuclear membrane are believed to have evolved from infolding in outer bacterial membranes.
Nucleus and Endoplasmic Reticulum Origin

- Infolding of the plasma membrane
- DNA
- Cell wall

Bacterial cell

- Prokaryotic ancestor of eukaryotic cells

Eukaryotic cell

- Nucleus
- Endoplasmic reticulum (ER)
- Nuclear envelope
Mitochondria and Chloroplasts

- Endosymbiotic Theory suggests a critical stage in the evolution of eukaryotic cells involved endosymbiotic relationships with prokaryotic organisms.
  - Energy-producing bacteria may have come to reside within larger bacteria, eventually evolving into mitochondria.
  - Photosynthetic bacteria may have come to live with larger bacteria, eventually forming chloroplasts in plants and algae.
Sexual Reproduction and Multicellularity

• Eukaryotic Cells possess the ability to sexually reproduce.
  - Permits frequent genetic recombination.

• Diversity was also promoted by multicellularity.
  - Fosters cell specialization.
Mass Extinctions, Asteroids and Climate Change

- **Mass extinctions**
  - Dramatic declines in a variety of species, families and phyla (>25%)
  - Timing of decline is concurrent
  - Rate of decline is precipitous (geological sense)
  - Example of catastrophism

- **Best example**
  - Cretaceous/Tertiary boundary (65 M years ago)
  - K-T boundary and Alvarez theory of catastrophism
Mass Extinctions, Asteroids and Climate Change: K-T Boundary

• Observations
  - Iridium deposits in distinct layers: suggestion of an asteroid (10-15 Km)
  - Other trace elements (characteristics of asteroids)
  - Shocked quartz
  - Soot deposits

• Conclusive Evidence
  - Impact crater 200 km off Yucatan Peninsula (Chicxulub Crater)
Mass Extinctions, Asteroids and Climate Change: Other examples

- Other mass extinctions
  - Five major extinctions over last 600 M years

- Evidence for gradualism
  - First principles: evolution
  - Pattern in the data
    - Recovery response
    - Overall increment in number of families over geological time

- Conclusions: Catastrophism coupled with gradualism
The hypothesis that an impact killed the dinosaurs seems

- A well supported by geological evidence.
- B an idea that once made sense but now can be ruled out.
- C just one of dozens of clear examples of impacts causing mass extinctions.
Evolutions of Humans

• Evidence for human evolution
  - Fossils
    • Differences throughout world
      - Out of Africa
    • Increase in brain volume and weight/mass ratio
  - Society
    • Changes in history
  - Civilizations
    • Technological developments
Artificial Life

• What is “artificial life”
• New organisms modified from existing organisms
• New organisms “created” from non-life
• Bioethics of artificial life
iClicker Question

• Which of the following is a likely benefit of creating artificial life?
  - A  We’ll gain insight into the origin of life on Earth.
  - B  The new life could eliminate our dependence on fossil fuels.
  - C  The technique could allow us to bring vanished species back to life.
Origin and Evolution of Life on Earth: Conclusions

• Plausible scenarios for the early origin of life on Earth (abiotic and biotic)
• Role of mutation and evolution in origin of increasingly more complex forms of metabolism
• Role of major evolutionary and climatological events as “pulses” of diversification in biota