A2.1 Origin of cells

Unity and diversity—Cells

Additional higher level: 2 hours

Guiding questions

• What plausible hypothesis could account for the origin of life?

• What intermediate stages could there have been between non-living matter and the first living cells?

Additional higher level

Note: There is no SL content in A2.1

A2.1.1—Conditions on early Earth and the pre-biotic formation of carbon compounds

Include the lack of free oxygen and therefore ozone, higher concentrations of carbon dioxide and methane, resulting in higher temperatures and ultraviolet light penetration. The conditions may have caused a variety of carbon compounds to form spontaneously by chemical processes that do not now occur.

- The study of the origin of cells explores how non-living chemical compounds gradually evolved into the first living cell(s)
- Conditions on **early, pre-biotic** (before life) Earth are likely different than the present:
  - **Lack of free oxygen**: O_2 was present in very small amounts because it reacted with other chemicals, like iron. Since ozone (O_3) is formed from oxygen, the ozone layer did not exist
    - **High levels of ultraviolet light** penetrated the atmosphere due to the absence of the ozone layer, which could have provided energy for some reactions to form carbon compounds
  - **High CO_2 and CH_4 (methane)** levels due to high volcanic activity & meteorites
    - Both are greenhouse gases that trap heat in the atmosphere & led to **high temperatures** that could have supplied energy for some reactions to form carbon compounds
- Pre-biotic conditions may have allowed chemical processes that do not normally occur on Earth today, enabling the spontaneous formation of a variety of carbon compounds that make up cells

A2.1.2—Cells as the smallest units of self-sustaining life

Discuss the differences between something that is living and something that is non-living. Include reasons that viruses are considered to be non-living.

- Understanding the differences between non-living and living things provides the theoretical framework necessary to guide research into the origin of cells
- **Cells** are the **smallest units** of self-sustaining life; they are able to independently perform the processes needed to carry out all life functions
- Something must independently carry out all life functions to be considered living
  - Viruses are considered non-living because they do not carry out all life functions independently

A2.1.3—Challenge of explaining the spontaneous origin of cells

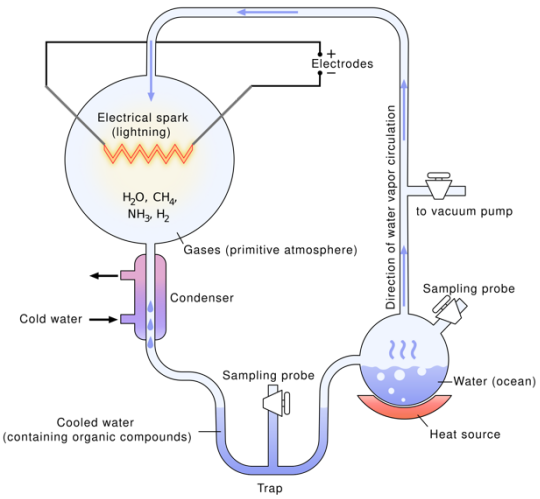
Cells are highly complex structures that can currently only be produced by division of pre-existing cells. Students should be aware that catalysis, self-replication of molecules, self-assembly and the emergence of compartmentalization were necessary requirements for the evolution of the first cells.

- The **spontaneous** origin of cells (the idea that they evolved from non-living matter) is challenging to explain since cells are highly complex structures that currently only form by division of pre-existing cells
- Certain processes had to develop as non-living matter gradually evolved into the first cells:
  - **Self-replication** of molecules to ensure continuity and heredity
  - **Self-assembly** of molecules into more complex structures (i.e. phospholipids self-assemble to lipid bilayers) as the first cells lacked the cell machinery needed to build organized structures
  - **Compartmentalization** to help control chemical processes
  - **Catalysis** to ensure chemical reactions occur fast enough to support life functions

A2.1.4—Evidence for the origin of carbon compounds

Evaluate the Miller–Urey experiment.

- The **Miller–Urey experiment** showed that organic molecules can be formed from inorganic compounds under conditions similar to pre-biotic Earth
  - Conceptual aspects:
    - The gas mixture (CO_2, CH_4, NH_3, H_2) in the flask represents the atmosphere of pre-biotic Earth
    - Electrodes are used to generate an electric spark to represent lightning (a source of energy)
    - A flask connected to the gas mixture represents oceans
  - Method:
    - The water is heated & its vapor is mixed with the electrified gas chamber
    - The gas mixture then passes through a condenser to cool the water vapor into a liquid, which is then sampled to analyze the presence of organic compounds
- Amino acids were found in the samples, showing that organic compounds can be formed from inorganic matter without living organisms
- There are several limitations to this experiment:
  - Does not explain how proteins could have formed from amino acids without living organisms
  - It was published in 1953 & the atmospheric model of pre-biotic Earth has changed since then
  - Does not show how other biomolecules (like sugars or lipids) could have been produced before cells



A2.1.5—Spontaneous formation of vesicles by coalescence of fatty acids into spherical bilayers

Formation of a membrane-bound compartment is needed to allow internal chemistry to become different from that outside the compartment.

- Compartmentalization is accomplished by membranes, which must have occurred spontaneously as a result of the chemical properties of phospholipids (fatty acids)
  - Formation of a membrane-bound compartment is needed to allow internal chemistry to become different from that outside the compartment, enabling metabolism as a life function to evolve
- Phospholipids are **amphipathic** (contain both **hydrophobic** & **hydrophilic** regions) so they tend to spontaneously **coalesce** (come together) to form hollow **spherical bilayers** for maximum stability in aqueous solutions
  - In pre-biotic Earth, these phospholipids most likely self-assembled into small spherical bilayers called **vesicles**, which may have eventually evolved into the first cells

NOS: Students should appreciate that claims in science, including hypotheses and theories, must be testable. In some cases, scientists have to struggle with hypotheses that are difficult to test. In this case the exact conditions on pre-biotic Earth cannot be replicated and the first protocells did not fossilize.

- Claims in science, including hypotheses and theories, must be testable & falsifiable
- In some cases, hypotheses are difficult to test because they involve phenomena that occurred billions of years ago like the hypothesis about the origin of cells where the exact conditions on pre-biotic Earth cannot be replicated
- **Protocells** are hypothetical cell-like structures that are proposed to have existed before cells as an intermediate stage between non-living and living things
  - They may have formed due to the self-assembly of early biomolecules but there is no evidence yet that they exist because no protocell fossils have been found thus far

A2.1.6—RNA as a presumed first genetic material

RNA can be replicated and has some catalytic activity so it may have acted initially as both the genetic material and the enzymes of the earliest cells. Ribozymes in the ribosome are still used to catalyse peptide bond formation during protein synthesis.

- Molecules that enable inheritance and regulation of cell functions must have been present as the first cell formed
- One prevalent hypothesis is that RNA is the presumed first genetic material & catalyst:
  - It can **spontaneously assemble** from nucleotides
  - It can form copies of itself (enabling **self-replication**)
  - It can act as a **catalyst** in chemical reactions (perhaps serving as enzymes of the earliest cells)
    - **Ribozymes** are RNA molecules in ribosomes that are still used to catalyse peptide bond formation during protein synthesis

A2.1.7—Evidence for a last universal common ancestor

Include the universal genetic code and shared genes across all organisms. Include the likelihood of other forms of life having evolved but becoming extinct due to competition from the last universal common ancestor (LUCA) and descendants of LUCA.

- Not all descendants of the first cell have lineages that survived until today; only the Last Universal Common Ancestor (LUCA) had surviving lineages that are hypothesized to have given rise to all life on modern Earth
  - It is likely that other forms of life have evolved from the first cells on Earth but became extinct due to competition from LUCA and its descendants
- **LUCA** is the most recent **population** of **single-celled organisms** from which all current life on Earth is descended from (bacteria, archaea, and eukaryotes). Evidence for its existence includes:
  - **Universal genetic code**: all organisms use the same codons to represent the same amino acids
    - This makes the existence of LUCA more plausible because it is highly unlikely that all organisms independently evolved the same genetic code from different ancestors
  - **Shared genes** across all organisms: some genes or sections of DNA are shared by all organisms because they have essential cell functions, like ribosomal proteins
    - This makes the existence of LUCA more plausible because it is likely that these shared genes are descendent from an ancestor that all organisms share

A2.1.8—Approaches used to estimate dates of the first living cells and the last universal common ancestor

Students should develop an appreciation of the immense length of time over which life has been evolving on Earth. Students should have a basic understanding of common approaches such as genomic analysis, fossils, and carbon dating.

- Estimating dates of the first cells and LUCA is difficult because cells do not fossilize easily & Earth's surface is constantly changing by heat & pressure
- Approaches used to estimate dates of the first cells & LUCA:
  - **Fossils**: ancient microorganisms formed layers of rock & sediment many years ago, which can be dated by radioisotopes to determine their age
    - Fossils do not directly identify LUCA or the first living cells but they provide a minimum date for early life which can help scientists estimate when life might have evolved
  - **Genomic analysis**: comparing DNA and protein sequences between organisms
    - DNA and protein sequences evolve at a relatively constant rate over time; sequence differences between organisms can be used as '**molecular clocks'** to estimate how long it has been since the species shared a common ancestor (e.g. LUCA)
    - A limitation of this method is that mutation rates are not constant across organisms
  - **Carbon dating**: radioactive carbon has a constant rate of decay that can be used to estimate the age of dead organisms by measuring the amount of radioactive carbon present in the sample
    - Helps scientists estimate when the first cells or LUCA might have existed

A2.1.9—Evidence for the evolution of the last universal common ancestor in the vicinity of hydrothermal vents
Include fossilized evidence of life from ancient seafloor hydrothermal vent precipitates and evidence of conserved sequences from genomic analysis.

• There is evidence that suggests that LUCA evolved in the vicinity of **hydrothermal vents** (cracks in the Earth's ocean floor where hot mineral water is released)
  • Fossils of ancient microorganisms have been found in the seafloor of hydrothermal vents, suggesting early life may (& LUCA) have evolved there
  • Hydrothermal vents are a high energy source that could have supported the formation of carbon compounds from inorganic matter
  • Genomic analysis of currently living organisms suggests that LUCA may have possessed genes related to anerobic metabolism that utilized the minerals of hydrothermal vents for energy

Linking questions

• For what reasons is heredity an essential feature of living things?

• What is needed for structures to be able to evolve by natural selection?

Review questions

- Define the Last Universal Common Ancestor (LUCA). [1]
- Define protocells. [1]
- Outline the evidence for the evolution of the Last Universal Common Ancestor (LUCA) in the vicinity of hydrothermal vents. [2]
- Explain why hypotheses about the origin of cells are difficult to test. [2]
- Outline the evidence for the existence of the Last Universal Common Ancestor (LUCA). [3]
- Discuss the differences between something that is living and something that is non-living. [4]
- Outline the different approaches used to estimate dates of the first living cells and the last universal common ancestor. [4]
- Explain why RNA is the presumed first genetic material. [4]
- Outline why pre-biotic Earth conditions may have caused a variety of carbon compounds to form spontaneously. [4]
- Evaluate the Miller–Urey experiment. [6]
- Explain how **three** biomolecules meet the necessary requirements for the evolution of the first cells. [8]
- Evaluate the claim that "all entities exist on a spectrum from non-living to living." [8]

References

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