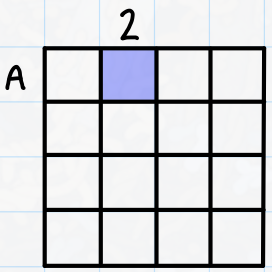
A2.1 Origins of Cells

Ver. 2

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?

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?



Theme: Unity and Diversity

Level of Organization: Cells

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Peter Marier

NOTEWORTHY SCIENCE

MARIER

https://pdb101.rcsb.org/sci-art/goodsell-gallery/abiogenesis

HL Learning Outcomes

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.
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.
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. **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.
A2.1.4	Evidence for the origin of carbon compounds	Evaluate the Miller–Urey experiment.
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.
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.
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.
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.
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.

HL

A2.1.2—Cells as the smallest units of self-sustaining life
A2.1.3—Challenge of explaining the spontaneous origin of cells

What does it mean to be 'alive'? A way of considering this question is to list what all living things do, i.e the processes of life. Cell structure A2.2 But these are what is required to maintain life, not life itself

↳ living things (unlike non-living) use ENERGY to keep themselves in an ordered state - they are **self-sustaining** ⟶ viruses are unable to maintain a steady state independently (require a host cell) .. ~~alive~~

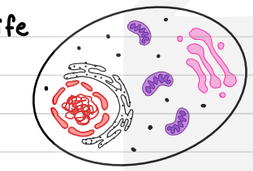
↳ living things pass the ability to maintain this highly-ordered state onto their offspring (reproduction) ⟶ viruses require a host to replicate .. ~~alive~~

↳ living things (at least on Earth) are composed of cells ⟶ viruses are not made of cells but a capsid surrounding genetic material - no internal metabolism .. ~~alive~~

viruses A2.3

Evolution + Speciation A4.1

Cell: the smallest unit of self-sustaining life
- ✓ use energy to maintain ordered state
- ✓ grow and divide to produce new cells
- ✓ performs all the functions of life



∴ alive

- x cell components are not self-sustaining
- x most cell components cannot self-replicate
- x individually cannot perform all functions of life

∴ ~~alive~~

NASA's definition of life:
"self-sustaining chemical system capable of Darwinian evolution"

Spontaneous Generation: early theory which posits that living creatures could appear from non-living matter, which is a common occurrence (ex: maggots from rotting meat or frogs from mud)

- Redi (1668) - falsified that maggots arose spontaneously from meat

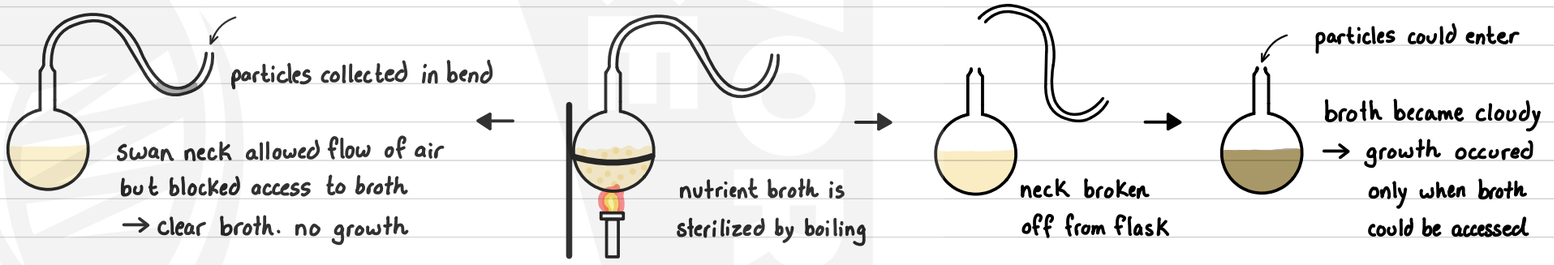
flies went to meat and maggots appeared

flies or air couldn't enter. No maggots

maggots appeared on gauze, not meat

Conclusion: maggots only appeared with presence of flies, not spontaneously

- Pasteur (1859) - falsified that a sterile nutrient broth could alone give rise to life - contamination from air was required



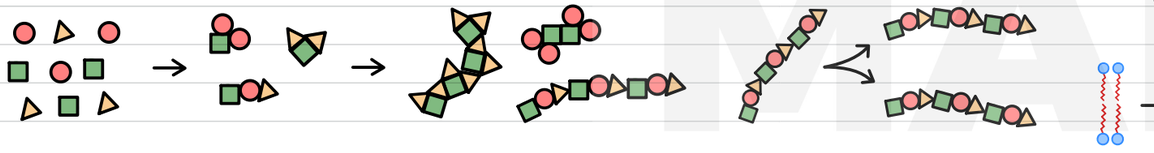
Conclusion: spontaneous generation does not occur currently and thus all cells must come from pre-existing cells - **biogenesis**

If cells can only be produced by division of pre-existing cells - how did the first cells come to be? ⟶ over a very long period of time, in incremental stages (not spontaneously or as a single event)

Abiogenesis: natural process where life arose from non-living matter such as simple organic compounds

↳ The evolution of the first cells via abiogenesis required the following (and proceeded in stages):

1. Non-living synthesis of simple organic molecules from inorganic molecules
2. self-assembly of larger, more complex polymers from simple organic molecules
3. Self-replication of molecules enabling inheritance and evolution
4. Compartmentalization through formation of membranes to enclose cell contents, allowing separation of internal and external environment (for homeostasis)



protocell

※ Catalysis is also required in order to control and speed up chemical reactions and metabolism

NOS: Claims in science (such as hypotheses and theories) must be testable

observations ⟶ research question ⟶ hypothesis ⟶ test ⟶ results

※ science requires hypotheses to be falsifiable and for data to be replicable

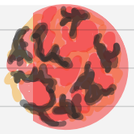
Some hypotheses are difficult (not impossible) to test such as abiogenesis:

↳ the exact conditions of pre-biotic Earth are unknown, thus any replication and test of these conditions are imperfect and carry uncertainty and doubt

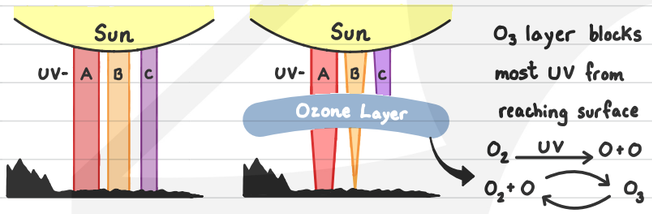
↳ the first protocells did not fossilize due to a lack in hard parts and rocks likely eroded or were altered from heat, thus direct evidence is missing

HL A2.1.1—Conditions on early Earth and the pre-biotic formation of carbon compounds A2.1.4—Evidence for the origin of carbon compounds A2.1.5—Spontaneous formation of vesicles by coalescence of fatty acids into spherical bilayers. A2.1.6—RNA as a presumed first genetic material

~4.5 billion years ago (gya) the Sun formed, followed soon after by the Earth and the Solar System. Early Earth had very different atmospheric conditions than today:



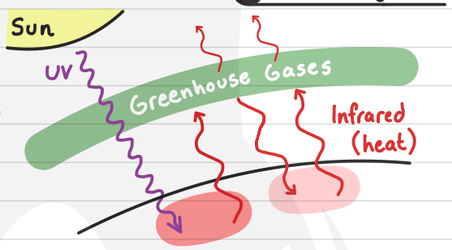
- lack of free oxygen (O_2)
  - ↳ no photosynthesis (no production) and any reacts with other elements such as iron
  - ↳ ozone (O_3) cannot form, ∴ allowing more solar ultraviolet light (UV) to hit the Earth's surface



※ our atmosphere today is ~21% O_2 with an ozone layer in the stratosphere

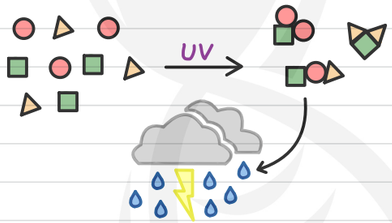
- high concentrations of carbon dioxide (CO_2) and methane (CH_4)
  - ↳ high levels due to much volcanic activity and meteorite bombardment
  - ↳ both are greenhouse gases: absorb and re-emit longwave radiation (heat)
  - ↳ intense greenhouse effect results in a lot of heat (emitted from the Earth's surface) being trapped in the atmosphere → higher temperatures
  - ↳ very high temperatures also resulted in frequent lightning storms

climate change D4.3



※ our atmosphere today is ~0.04% CO_2 and ~0.00019% CH_4. The majority is Nitrogen (N_2) at ~78%

These very harsh and different conditions in early pre-biotic Earth may have enabled the spontaneous formation of carbon compounds (i.e. biomolecules) via chemical processes which do not occur today:



↳ high-energy UV light can destroy molecules into smaller, more reactive parts, allowing the formation of larger, more complex molecules

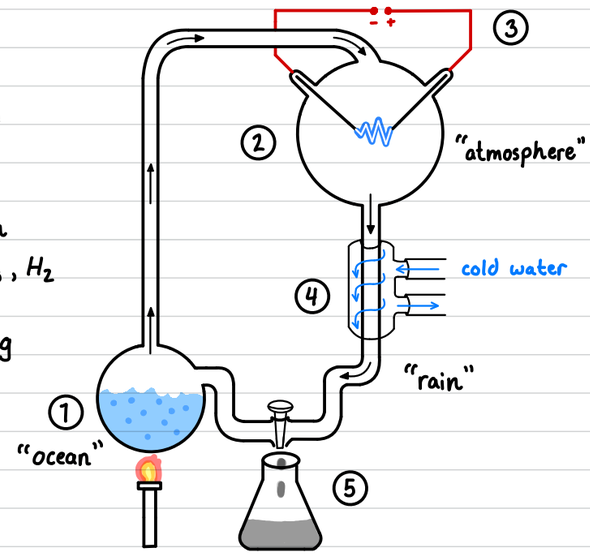
↳ substances produced dissolve in water in the atmosphere and are deposited as rainfall into pools/oceans creating a "soup" of carbon compounds

Miller-Urey Experiment - 1952

Goal: replicate pre-biotic Earth conditions and observe if organic carbon compounds could be produced

Methodology

1. Flask with water is boiled to simulate evaporation during water cycle and Earth's high temperatures
2. Water vapour enters flask containing gases which replicate pre-biotic reducing atmosphere: CH_4, NH_3, H_2
3. Electrodes generate sparks which mimic lightning
4. Condenser cools gases. Water becomes liquid and dissolves molecules
5. Periodically, samples are collected for analysis



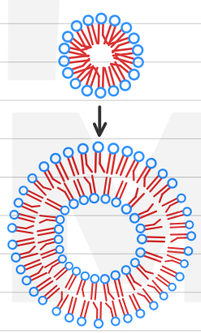
Results: After 1 week the sample was dark and found to contain organic molecules such as amino acids

Evaluation - make an appraisal by weighing up the strengths and limitations

✓ highly repeatable methodology - experiment has been replicated with similar results	× composition of tested atmosphere was incorrect - should have a lot more CO_2 and less NH_3 and CH_4
✓ variables can be altered (ex: gas composition or energy source) with similar results	× main energy source likely UV radiation (due to lack of O_3) and not lightning

Amphipathic molecules have both hydrophilic (polar) and hydrophobic (non-polar) properties lipids B1.1

↳ When in contact with water their hydrophilic end will face water and their hydrophobic tails are pushed away, spontaneously forming micelles which can coalesce into spherical bilayer vesicles (trapping fluid and molecules)



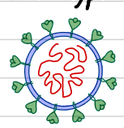
※ fatty acids likely formed the first membranes due to their simplicity

↳ The formation of bilayer membranes provides a boundary between the inside of vesicle and the external environment i.e compartmentalization

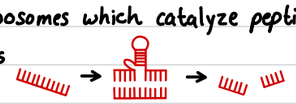
↳ Allows the internal chemistry to differ from surroundings - crucial for homeostasis

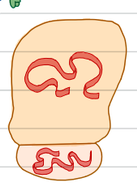
RNA is presumed to have been the first genetic material used by protocells - RNA World hypothesis

↳ like DNA, RNA stores genetic information which can be used to synthesize proteins
ex: some viruses (like SARS-CoV-2 and HIV) still use RNA as genetic material



↳ RNA can act as a catalyst for chemical reactions
ex: ribozymes (ribonucleic acid enzymes) are RNA in ribosomes which catalyze peptide bonds
ex: ribozymes can cut RNA at specific base sequences



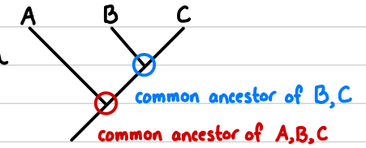


↳ RNA may be able to catalyze its own replication (unlike DNA which requires several protein enzymes)
furthermore, RNA mutates readily which can lead to variation and evolution

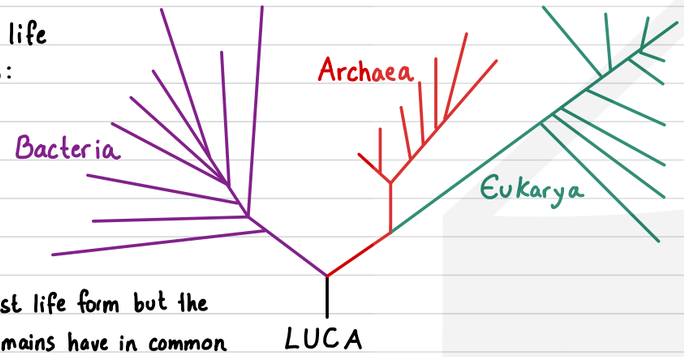
HL — A2.1.7—Evidence for a last universal common ancestor. A2.1.8—Approaches used to estimate dates of the first living cells and the last universal common ancestor. A2.1.9—Evidence for the evolution of the last universal common ancestor in the vicinity of hydrothermal vents

All life on Earth today is hypothesized to be descended from a single species - the **Last Universal Common Ancestor (LUCA)**

※ common ancestor = most recent species from which 2 or more species have evolved



Phylogenetic tree of life showing 3 Domains:



Cladistics A3.2

※ LUCA is not the first life form but the most recent all 3 domains have in common

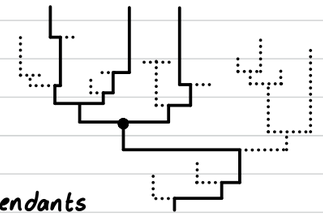
Evidence for a LUCA

Cladistics A3.2

- All organisms (and viruses) use the same universal genetic code (with only minor variations)
  - ↳ more likely this code evolved once (in LUCA) and was passed down rather than it evolving identically independently multiple times

Protein synthesis D1.2

- hundreds of genes are common in all organisms with relatively minor variations
  - ↳ unlikely the same base sequence, coding for the same protein evolved independently multiple times
  - ∴ shared genes likely originated in LUCA and were inherited

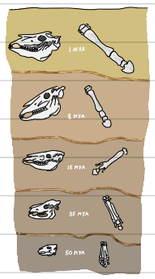


※ likely other lifeforms also evolved but became extinct due to competition from LUCA and/or its descendants

Different approaches to estimating dates of past biological events/activity

Fossils: remains or impression of a once-living organism from the past

↳ law of superposition: due to sedimentation, new materials are deposited over older ones ∴ the deeper the layer, the older it is and the materials therein

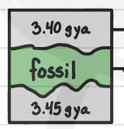


- **Stromatolites**: layered sedimentary formations formed from mats of photosynthetic cyanobacteria in shallow seawater. They secrete $CaCO_3$ which traps sediments, forming fossils layer by layer

ex: Strelley Pool Formation in Australia has been dated to be ~ 3.43 gya

※ fossilization is generally a rare, chance event and not all tissues fossilize

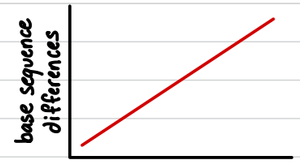
- **Radiometric dating**: technique where trace radioactive impurities in materials are dated by comparing the abundance of radioactive isotope to its decay products (ex: $^{14}_{6}C \rightarrow {}^{14}_{7}N$)
  - ↳ different isotopes have known rates of decay (½ life = amount of time for half of atoms to decay)
  - ex: $^{14}_{6}C$ only dates samples up to ~60,000 years



ex: ^{238}U to ^{206}Pb has a half-life of 4.5 billion years
- → the more ^{206}Pb, the older the specimen
- → measure $^{238}U/^{206}Pb$ in rocks to determine age
- ∴ fossils within/around these rocks are ~ this age
- → in this case, between 3.40 and 3.45 gya, i.e. ~ 3.425 gya

- **Molecular clock**: genomic base sequences from different species are compared for similarity and used to estimate time since divergence
  - ↳ mutations cause change in DNA which can be inherited and these accumulate over time. The rate these occur can be determined and used to estimate how long ago species diverged from a common ancestor

ex: if mutation rate for a gene is 1 base pair every 100,000 years and two species have 6 differences they diverged ~ 600,000 years ago



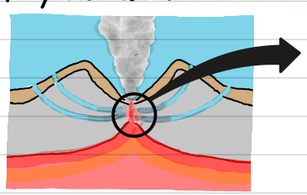
※ using this technique, LUCA lived ~ 4.2 gya

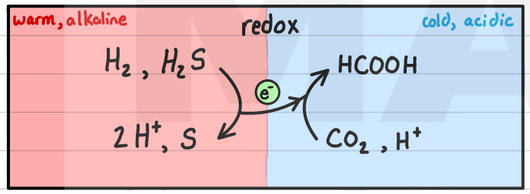
Evidence for LUCA first evolving in the vicinity of hydrothermal vents

hydrothermal vents are fissures (openings) in the deep sea floor where geothermally-heated, mineral-rich (reduced inorganic chemicals) water is discharged

alkaline hydrothermal vents (ex: 'Lost city' field) have conditions suitable to the origin of life:

- warm temperatures - hot enough to drive reactions but cool enough that organic molecules aren't destroyed
- rich in reduced chemicals (H_2, CH_4, H_2S) that supply both energy and materials for polymerization of chemicals (ex: fatty acids used in membranes)
- natural redox-pH gradient drives reduction of CO_2 into organic molecules

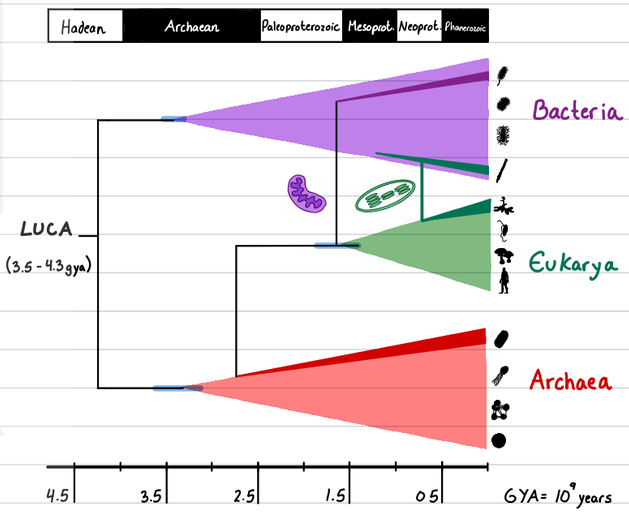




among the oldest fossilized traces of life have been found at hydrothermal vents where precipitates (like those produced by microorganisms) have been dated to be at least 3.77 gya

genomic analysis of hundreds of conserved genes suggest LUCA shared many genes (and thus characteristics) in common with extremophiles living at deep-sea vents:

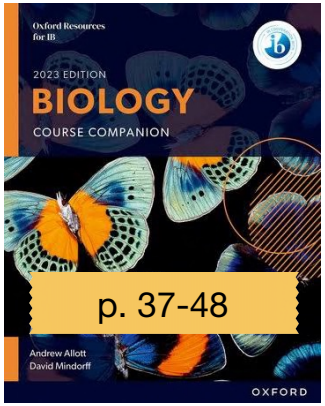
- ↳ anaerobic metabolism (lived without oxygen)
- ↳ thermophilic (tolerant to high temperatures)
- ↳ chemoautotrophic: could fix CO_2 and nitrogen to build biomolecules



Resource Links

each resource is hyperlinked

Textbooks



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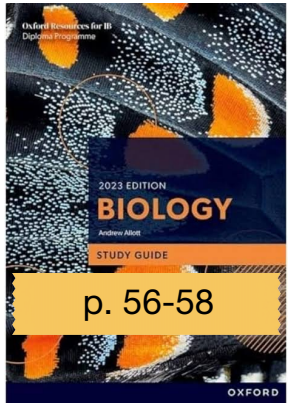

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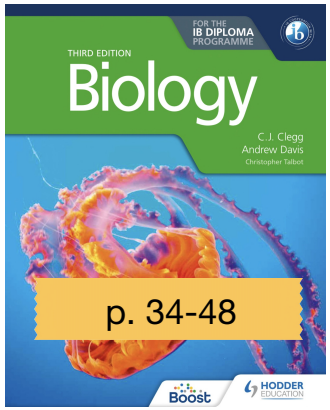

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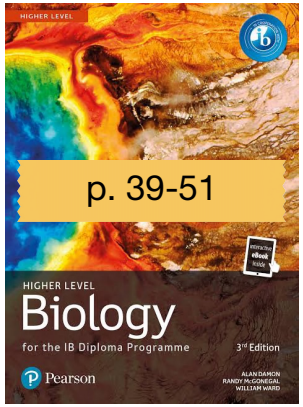

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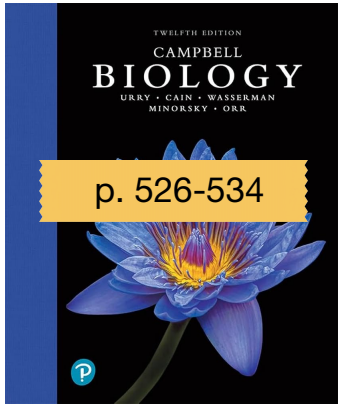

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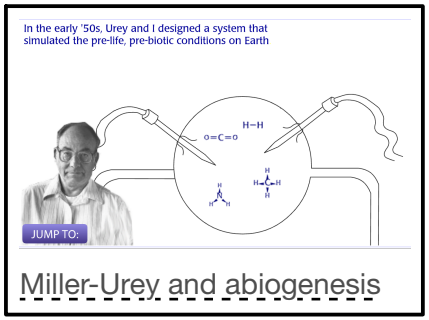
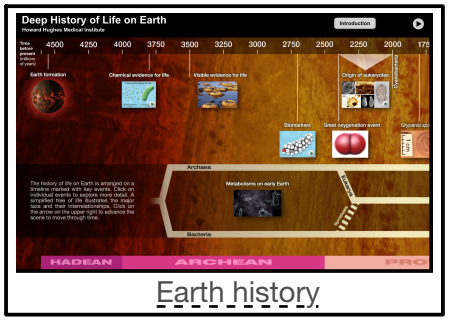
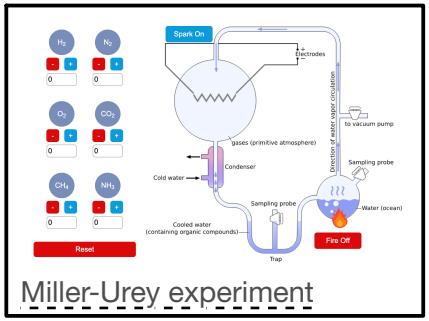
Simulators / Interactives



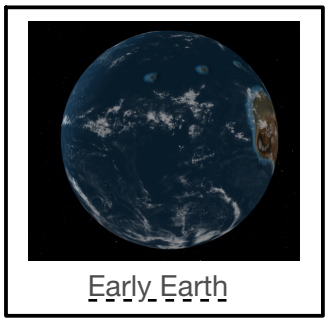
Miller-Urey and abiogenesis



Earth history



Miller-Urey experiment



Early Earth

Articles

Betts, H. C., Puttick, M. N., Clark, J. W., Williams, T. A., Donoghue, P. C. J., & Pisani, D. (2018). Integrated genomic and fossil evidence illuminates life's early evolution and eukaryote origin. Nature Ecology & Evolution, 2(10), 1556–1562. https://doi.org/10.1038/s41559-018-0644-x

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Lambert, J. (2024, November 20). All life on Earth today descended from a single cell. Meet LUCA. | Quanta Magazine. Quanta Magazine. https://www.quantamagazine.org/all-life-on-earth-today-descended-from-a-single-cell-meet-luca-20241120/

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