

A2.1 Origins of Cells

Guiding Questions

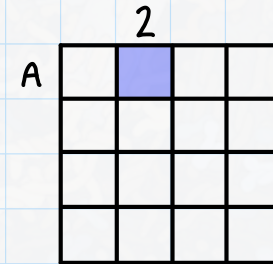
What plausible hypothesis could account for the origin of life?

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

Written and drawn by:

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HL Learning Outcomes

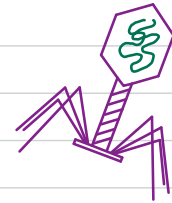
A2.1.1	Conditions on early Earth and the pre-biotic formation of carbon compounds	Include the lack of free oxygen and therefore ozone, higher concentrations of carbon dioxide and methane, resulting in higher temperatures and ultraviolet light penetration. The conditions may have caused a variety of carbon 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.
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.

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) .. **not alive**

↳ living things pass the ability to maintain this highly-ordered state onto their offspring (reproduction) → viruses require a host to replicate .. **not 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 .. **not alive**

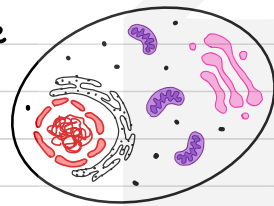


viruses A2.3

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**

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



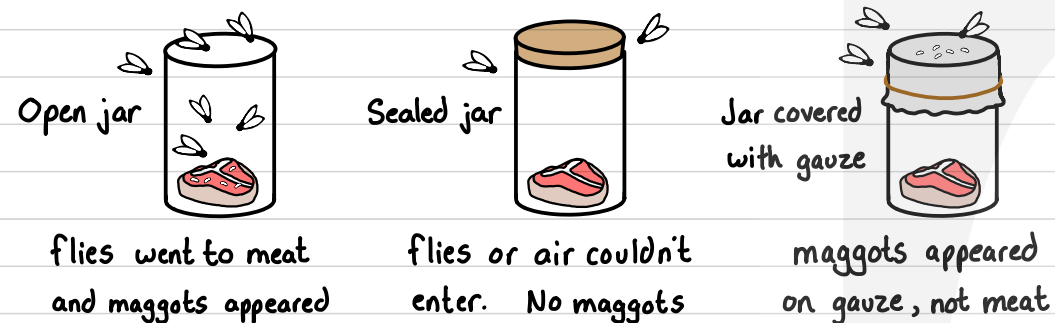
∴ **not alive**

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

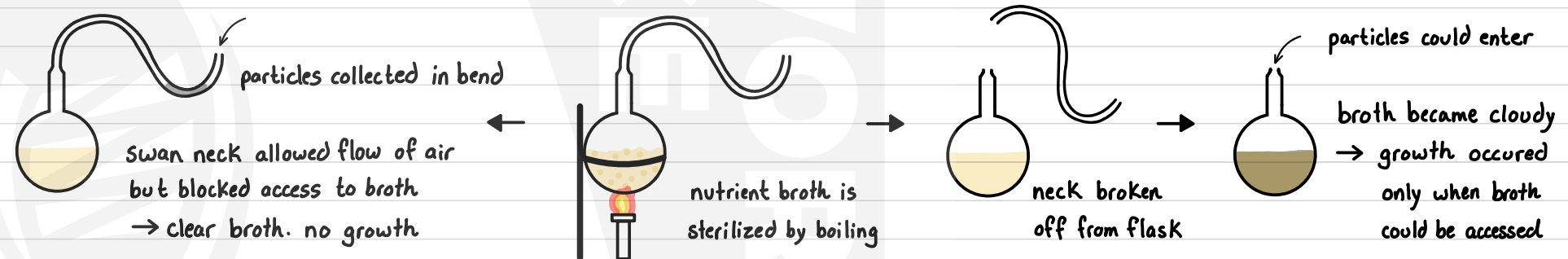


Spontaneous Generation: early theory which posits that living creatures could appear from non-living matter, which is a common occurrence (ex: maggots from rotting meat or frogs from mud)

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



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



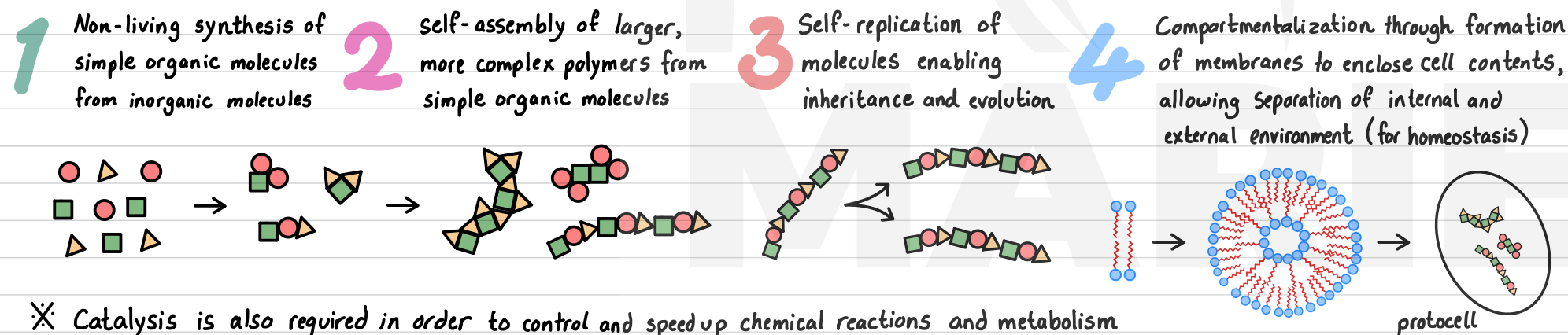
Conclusion: maggots only appeared with presence of flies, not spontaneously

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):



✗ 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

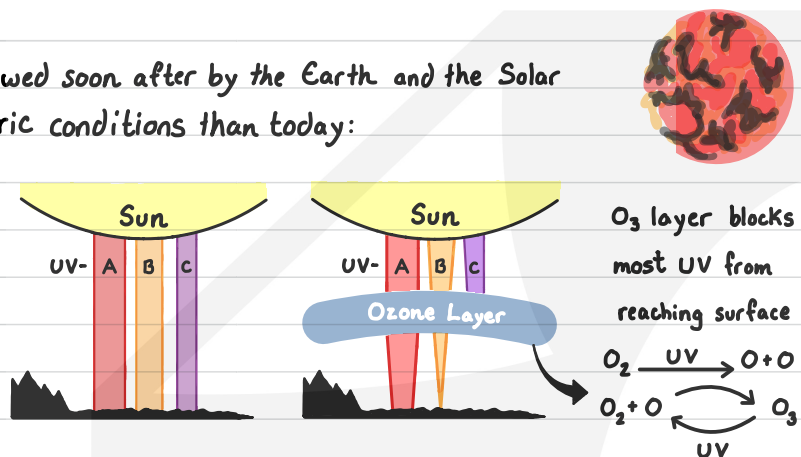
Some hypotheses are difficult (not impossible) to test such as abiogenesis:

↳ 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

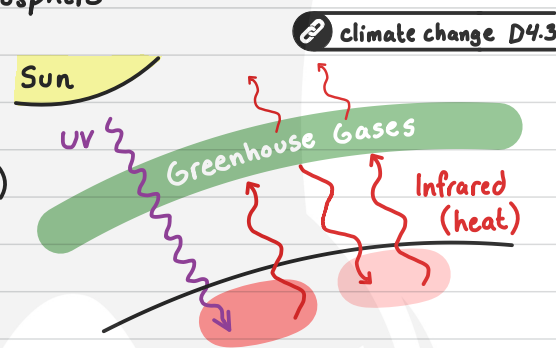
~4.5 billion years ago (gya) the Sun formed, followed soon after by the Earth and the Solar System. Early Earth had very different atmospheric conditions than today:

- lack of free oxygen (O_2)
 - no photosynthesis (no production) and any reacts with other elements such as iron
 - ozone (O_3) cannot form, $\therefore$ 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

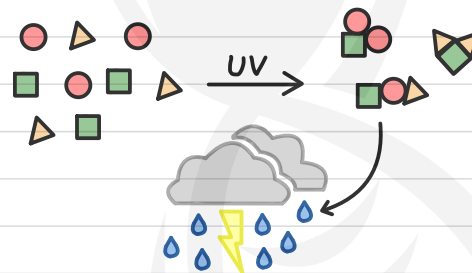
- high concentrations of carbon dioxide (CO_2) and methane (CH_4)
 - high levels due to much volcanic activity and meteorite bombardment
 - both are **greenhouse gases**: absorb and re-emit longwave radiation (heat)
 - intense greenhouse effect results in a lot of heat (emitted from the Earth's surface)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



✗ our atmosphere today is ~0.04% CO_2 and ~0.00017% 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

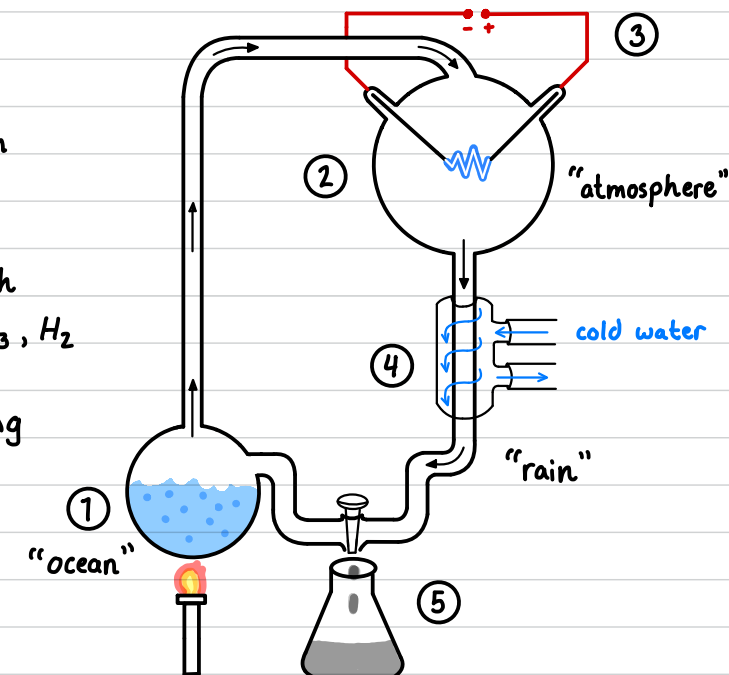


Miller-Urey Experiment - 1952

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

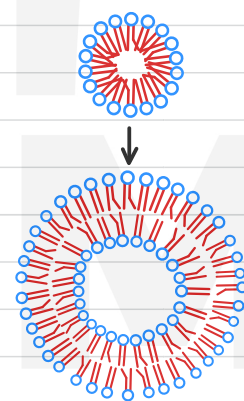
Evaluation - make an appraisal by weighing up the **strengths** and **limitations**

- | | |
|--|---|
| ✓ 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 end will repel naturally, spontaneously forming micelles which can coalesce into spherical bilayer vesicles (trapping fluid and molecules)



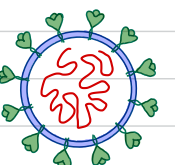
- The formation of bilayer membranes provides a boundary between the inside of vesicle and the external environment i.e. compartmentalization

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

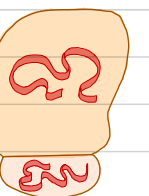
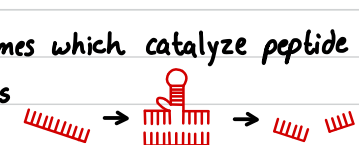
✗ fatty acids likely formed the first membranes due to their simplicity

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 enzymes) are RNA in ribosomes which catalyze peptide bonds
ex: ribozymes can cut RNA at specific base sequences

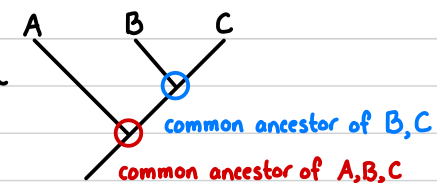


- RNA can self-replicate (unlike DNA which requires several protein enzymes) furthermore, RNA mutates readily which can lead to variation and evolution

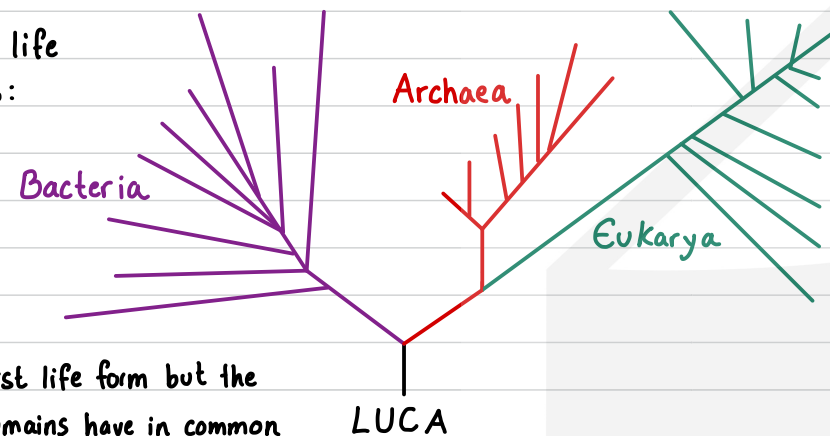
All life on Earth today is hypothesized to be descended from a single species – the

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:



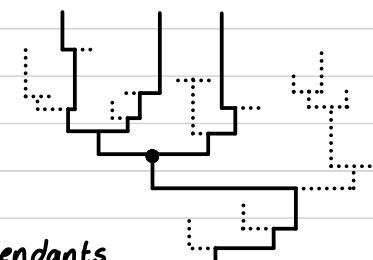
Cladistics A3.2

Evidence for a LUCA

Cladistics A3.2

Protein synthesis D1.2

- 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
- 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

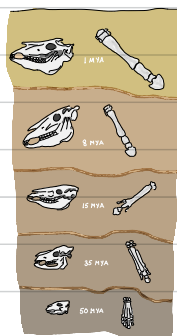
✗ LUCA is not the first life form but the most recent all 3 domains have in common

LUCA

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

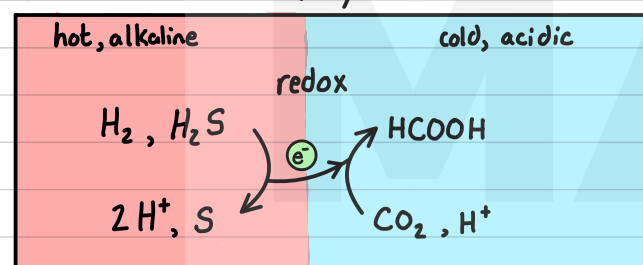
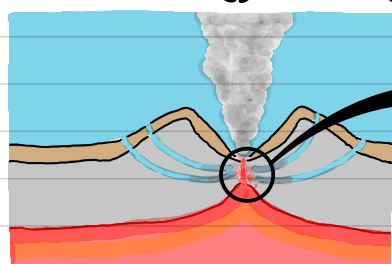


✗ fossilization is generally a rare, chance event and not all tissues fossilize

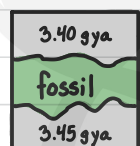
Evidence for LUCA first evolving in the vicinity of hydrothermal vents

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

- alkaline vents (white smokers) have conditions suitable to the origin of life: high temperatures and high concentration of hydrogen, methane, ammonia, and sulfides provide sources of energy for the polymerization of chemicals (ex: fatty acids used in membranes)



- **Radiometric dating**: technique where trace radioactive impurities in materials are dated by comparing the abundance of radioactive isotope to its decay products (ex: $^{14}_6\text{C} \rightarrow ^{14}_7\text{N}$)
→ different isotopes have known rates of decay ($\frac{1}{2}$ life = amount of time for half of atoms to decay)



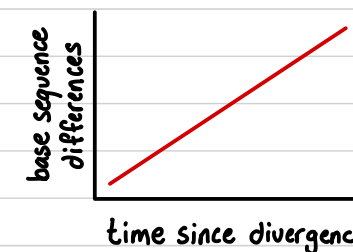
- ex: ^{238}U to ^{206}Pb has a half-life of 4.5 billion years
→ the more ^{206}Pb , the older the specimen
→ measure $^{238}\text{U}/^{206}\text{Pb}$ in rocks to determine age
∴ fossils within/around these rocks are ~ this age
→ in this case, between 3.40 and 3.45 gya, i.e. ~ 3.425 gya

- **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

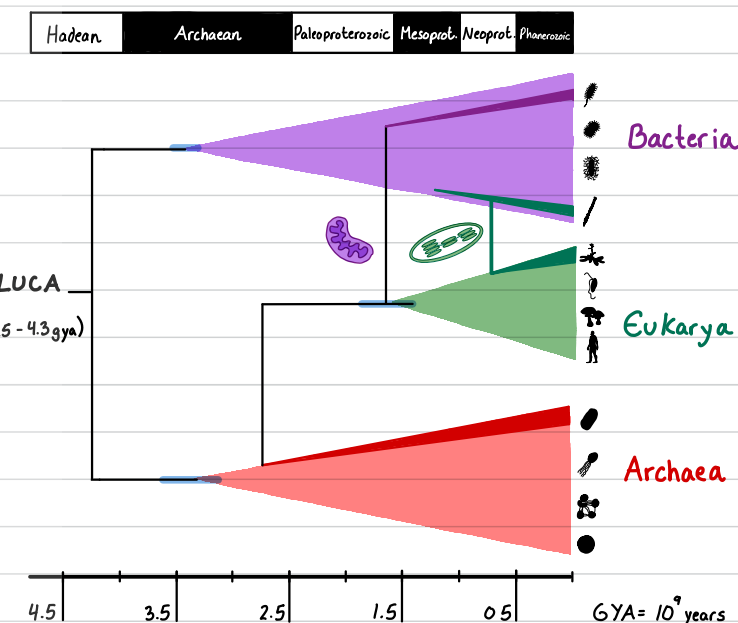
✗ using this technique, LUCA lived ~ 4.2 gya



- 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:

- underwent anaerobic metabolism (no oxygen)
- thermophilic (survives in extreme heat)
- chemoautotrophic: could fix CO_2 and nitrogen to form biomolecules

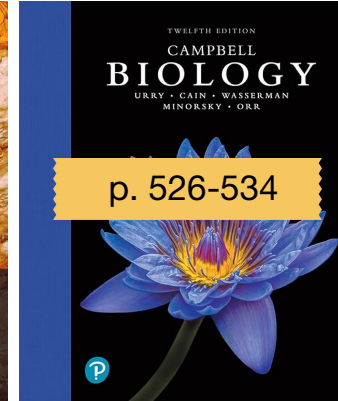
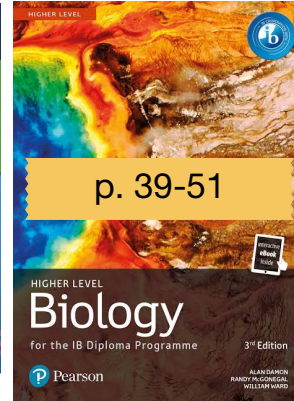
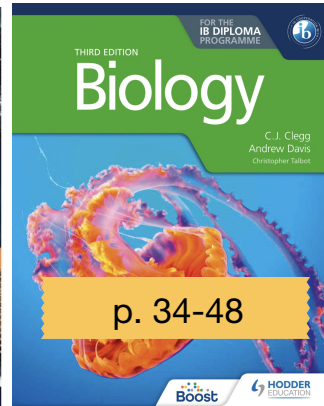
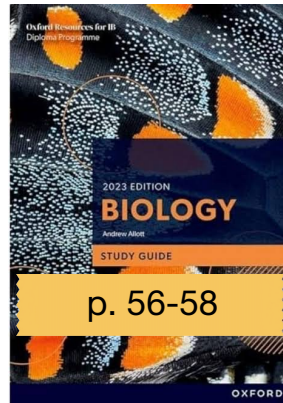
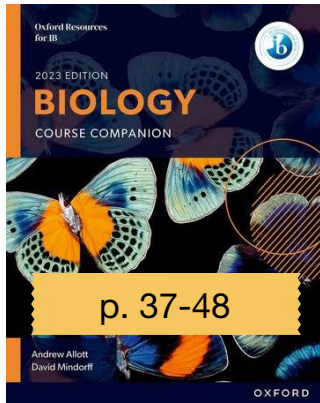


Resource Links

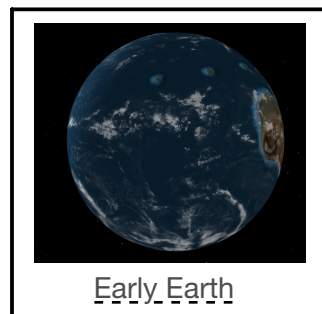
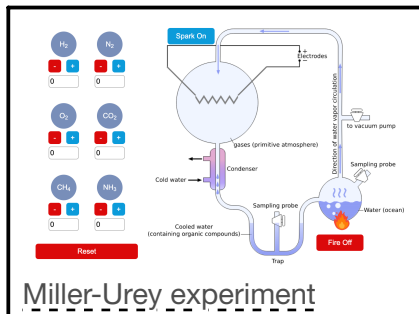
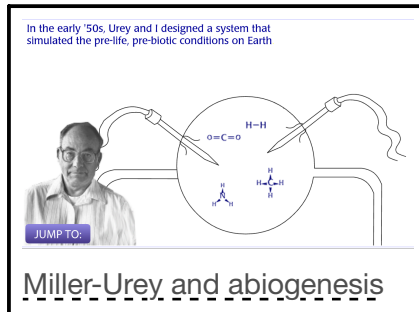
each resource is hyperlinked



Textbooks



Simulators / Interactives



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>

Cleland, C. E., & Chyba, C. F. (2002). Defining “life”. *Origins of Life and Evolution of Biospheres*, 32(4), 387–393. <https://doi.org/10.1023/a:1020503324273>

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

Machery, E. (2011). Why I stopped worrying about the definition of life. . . and why you should as well. *Synthese*, 185(1), 145–164. <https://doi.org/10.1007/s11229-011-9880-1>

Moody, E. R. R., et al. (2024). The nature of the last universal common ancestor and its impact on the early Earth system. *Nature Ecology & Evolution*, 8(9), 1654–1666. <https://doi.org/10.1038/s41559-024-02461-1>

Saito, H. (2022). The RNA world ‘hypothesis.’ *Nature Reviews Molecular Cell Biology*, 23(9), 582. <https://doi.org/10.1038/s41580-022-00514-6>

Weiss, M. C., Preiner, M., Xavier, J. C., Zimorski, V., & Martin, W. F. (2018). The last universal common ancestor between ancient Earth chemistry and the onset of genetics. *PLoS Genetics*, 14(8), e1007518. <https://doi.org/10.1371/journal.pgen.1007518>