A2.1 Cell Origins

Syllabus Content

1HL **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 carbon compounds to form spontaneously by chemical processes that do not now occur.

2HL **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.

3HL **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. 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 perhaps did not fossilize.

4HL **Evidence for the origin of carbon compounds**
Evaluate the Miller–Urey experiment.

5HL **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.

6HL **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.

7HL **Evidence for a last universal common ancestor (LUCA)**
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 LUCA and descendants of LUCA.

8HL **Approaches used to estimate dates of the first living cells and LUCA**
Gain appreciation for the immense length of time over which life has been evolving on Earth.

9HL **Evidence for the evolution of LUCA 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.

Guiding Questions

What plausible hypothesis could account for the origin of life?
What intermediate stages were there 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?

1HL Conditions on early Earth and the pre-biotic formation of carbon compounds

Earth formed well after the Big Bang in a cloud of spinning dust and gas about 4.5 billion years ago.

The oldest rocks appear to show the early atmosphere was:
- lower in free oxygen and later as it was produced it reacted with iron to form red iron oxide
- higher in methane due to volcanic eruptions and meteorites
- higher in carbon dioxide due to volcanic eruptions

reducing atmosphere – air low in oxygen and high in electron donors (H_2, H_2S, CO, CH_4, NH_3)

Oxygen is very reactive and breaks chemical bonds by taking electrons off other substances.
Low oxygen would mean low ozone (O_3) levels that protect against UV light.
The 100 times greater UV radiation and extra lightning may have provided activation energy for chemical reactions. However, UV light would also at the same time degrade organic molecules.

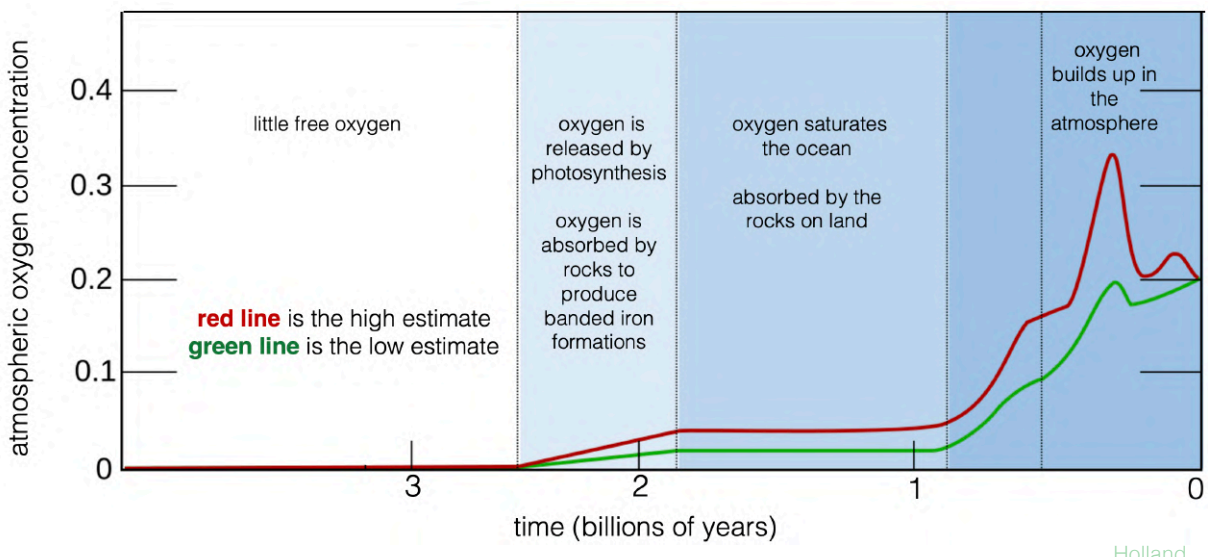
Temperature may have been higher due to:
- the greenhouse gases of methane (CH_4) and carbon dioxide (CO_2)
- asteroid strikes

The pH of the prebiotic oceans is unknown – it may have been pH 5 – pH 11.

Carbon containing compounds:
- may have spontaneously formed in hot springs, hydrothermal vents, and in clouds
- scientists are unsure which ones formed on their own
- may have rained down into pools, lakes, and oceans creating a primordial soup
- they likely included monomers that eventually formed sugars, proteins, lipids and nucleic acids

It is thought that once living things arose, they began to change the environment:
- oxygen levels increased due to photosynthesis allowing an ozone layer to protect against UV
- carbon dioxide levels decreased due to photosynthesis
- today any organic compounds that form are rapidly degraded by oxygen and UV light so the processes that formed life on Earth are no longer possible

Great Oxygenation Event



Holland

2HL Cells are the smallest unit of life

Living things carry out:

Movement
Respiration
Homeostasis
Growth
Reproduction
Excretion
Nutrition

Viruses cannot carry out independent *reproduction* because they lack *cellular machinery* therefore, they need a host cell to survive. For this reason they are not considered to be alive. Viruses do not grow they are assembled. With no metabolism they have no nutrition, homeostasis or metabolic waste for excretion.

It is observed that on earth all living things are made of cells.
Cells:

- can use energy
- can die
- can be removed from a multicellular organism and be cultured in the lab on their own
- parts of a cell cannot sustain life on their own
  - *therefore, the smallest unit of life is the cell*
- are highly ordered and self-sustaining
- currently the only way to produce a cell is by cell division from a living cell
- can pass on information to maintain a highly ordered state
- can reproduce
  - *therefore, all cells come from pre-existing cells*

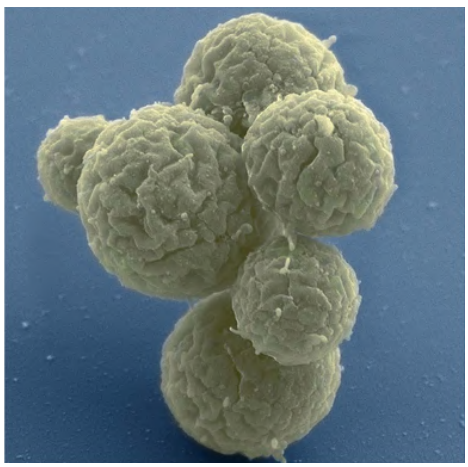
Cell Theory

- all life is made of one or more cells
- cells are the smallest unit of life
- all cells come from pre-existing cells

Recall that a theory in science is a well substantiated explanation.

One of the simplest cells is a bacterium called *Mycoplasma genitalium*, which has about 482 genes. It is an obligate parasite requiring a host cell as it has lost the genes to synthesize certain nutrients.

Synthetically produced DNA matching the digitally stored genome of *M. genitalium* was inserted into a *Mycoplasma* cell that had its DNA removed - creating an 'artificial synthetic cell'. By deleting further genes and testing these cells in a nutrient rich environment it is thought that 473 genes are essential for this cell to grow and divide.



Indiana University

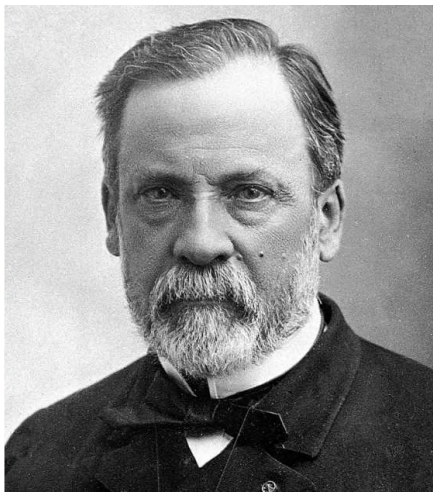
What may life look like on another planet?
NASA defines life as a self-sustaining chemical system capable of Darwinian evolution.

Three key aspects to life are energy, metabolism and information.

3HL Challenge of explaining the spontaneous origin of cells

spontaneous generation - theory from Aristotle 322BC that life can rapidly form from non-living matter

Microbes were once believed to come from wet hay, fleas from dust and maggots from meat.



Britannica

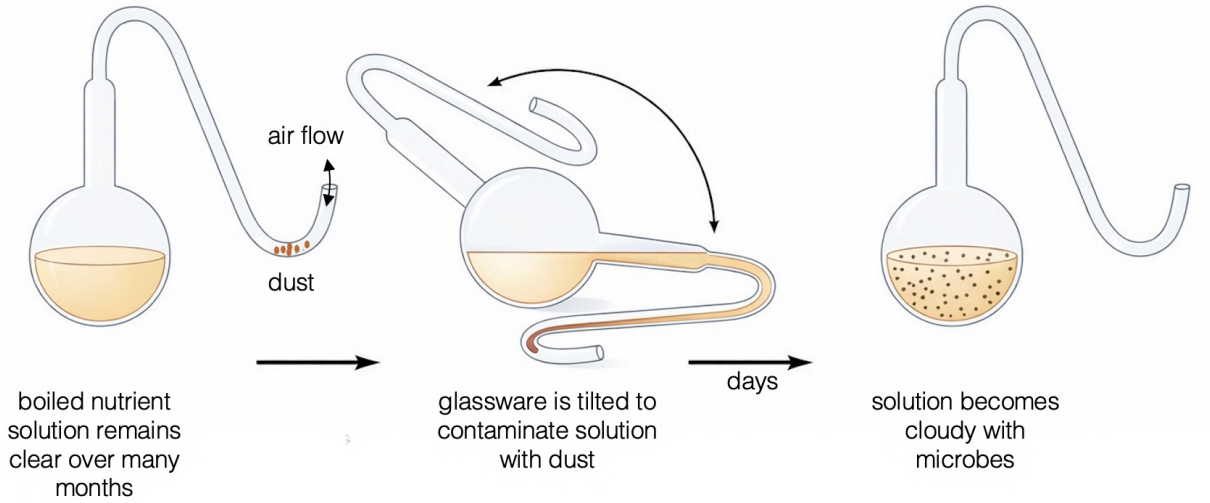
Louis Pasteur (1861) designed an experiment to test whether sterile nutrient broth could spontaneously generate microbial life – if in contact with a *vital force* present in the air.

He added nutrient broth to flasks then bent the necks into S - shapes that were open to the air.
Each flask was sterilized by boiling the broth to kill all microbes.

Conclusion:
- broth remained sterile unless particles entered from the air
- growth of microbes required a source of contamination
- microbes only come from (airborne) microbes

Pasteur refuted the hypothesis of spontaneous generation.
However, it is argued that he did not disprove abiogenesis.

abiogenesis - origin of life from non-living matter *gradually* over a *long period of time*



adapted from Pearson 2004

Cells are highly complex and can currently only be produced by division of pre-existing cells.

Some of the challenges of abiogenesis are:
- self-assembly of monomers and polymers - such as amino acids into proteins without enzymes
- self-replication of molecules (RNA/DNA)- enabling inheritance of successful variants (selection)
- emergence of cell membrane compartments - isolate chemical processes and conditions
- catalysis – enzymes control which chemical reactions occur and their speed

NOS
Claims in science, including hypotheses and theories, must be testable.
In some cases, scientists have to struggle with hypotheses that are difficult to test.
Exact conditions on pre-biotic Earth may not be known and the first protocells perhaps did not fossilize.

experimental science - is repeatable and testable using measurable data

forensic science - is not fully repeatable or testable using measurable data and a scientists' worldview becomes important when interpreting the evidence

hypothesis - falsifiable and testable prediction of how a system will behave under certain conditions

theory - in science a theory is a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses

falsification – use of the empirical (experimental) method to disprove a scientific hypothesis

Optional Extension (not required for the IB exam)

methodological naturalism – view that science restricts itself to natural causes only
This leaves open the possibility that higher dimensions and beings exist beyond time and space.

metaphysical naturalism – view that only the natural exists, the supernatural does not exist
This view does not leave open the possibility of a higher intelligence or outside intervention.
Love, thoughts, consciousness and the conscience are due to chemical reactions.

"The Cosmos is all that is or ever was or ever will be." C. Sagan

Should we be able to follow the evidence where ever it leads?

Other views on the origin of life include:
- undirected panspermia theory – life was randomly seeded by alien life
- directed panspermia theory – life was seeded on earth by alien life
- intelligent design theory – life has an intelligent cause than by undirected processes
- theistic – life was designed by God/s
- theistic evolution – life was evolved by God/s

Six criteria to identify high to low confidence science:
1. is the evidence repeatable
2. can the evidence be directly measured / observed
3. was the evidence obtained through a prospective study
4. was bias minimized
5. were assumptions minimized and openly disclosed
6. were reasonable claims made?

criteria from Stadler also see Long Story Short

If minds are wholly dependent on brains, and brains on biochemistry,
and biochemistry (in the long run) on the meaningless flux of the atoms,
I cannot understand how the thought of those minds should have any more significance than the sound of the wind in the trees.
C. S. Lewis

4HL Evidence for the Origin of Carbon Compounds

Living things contain these key elements - CHONPS.
Due to volcanic activity, it is assumed the early atmosphere contained:
Hydrogen (H_2), nitrogen (N_2), water (H_2O), methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S)

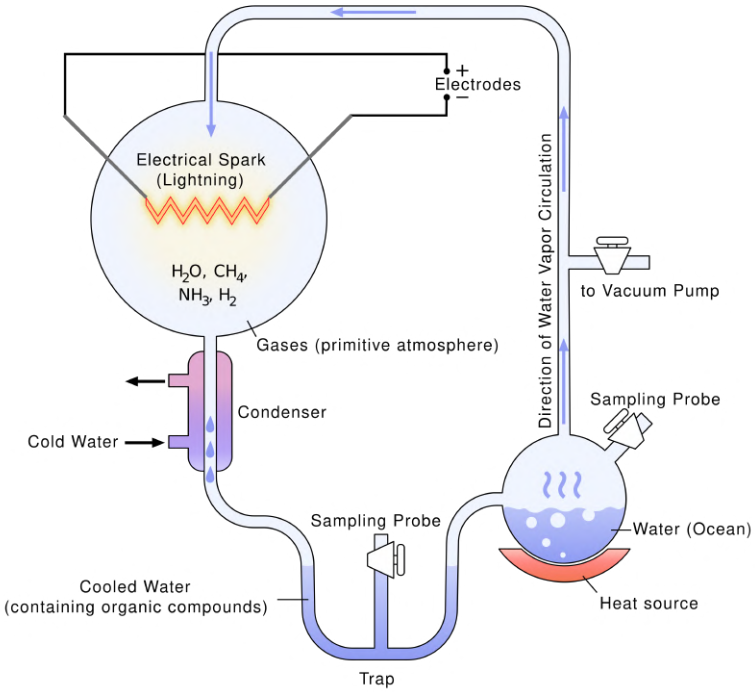
These monomers mixed together in a primordial soup – shallow oceans filled with chemicals where they may have reacted to form carbon containing organic compounds found in cells.

Miller and Urey 1953:

- tried to model early atmosphere conditions in the lab
- testing idea of 'chemical evolution'- formation of organic compounds from inorganic chemicals
- mixed methane, hydrogen, ammonia and water in a flask – similar to early atmosphere
- heated the water – similar to volcanic heat
- sparked electricity through the gases – like lightning

After a week they discovered the spontaneous origin of:

- 5 of the twenty amino acids – later tests of their vials found 14 amino acids and 5 amines
- 15% of the carbon had become organic compounds



Carny

Evaluation of Miller and Urey Experiment:
strengths

- some organic molecules useful for life can form abiotically from simple gases and energy
- provided a basis for further research

limitations

- nearly 99% of the chemicals formed were a toxic tar-like substance
- useful substances were very dilute
- they did not use UV light which breaks down methane and ammonia
- left out phosphorous which is needed for life (as ATP) but is also very reactive
- formed a mix of left and right-handed molecules – cells require left-handed molecules
- gas from volcanoes has little methane or ammonia
- they did not calculate the probability of molecules forming in the correct sequence

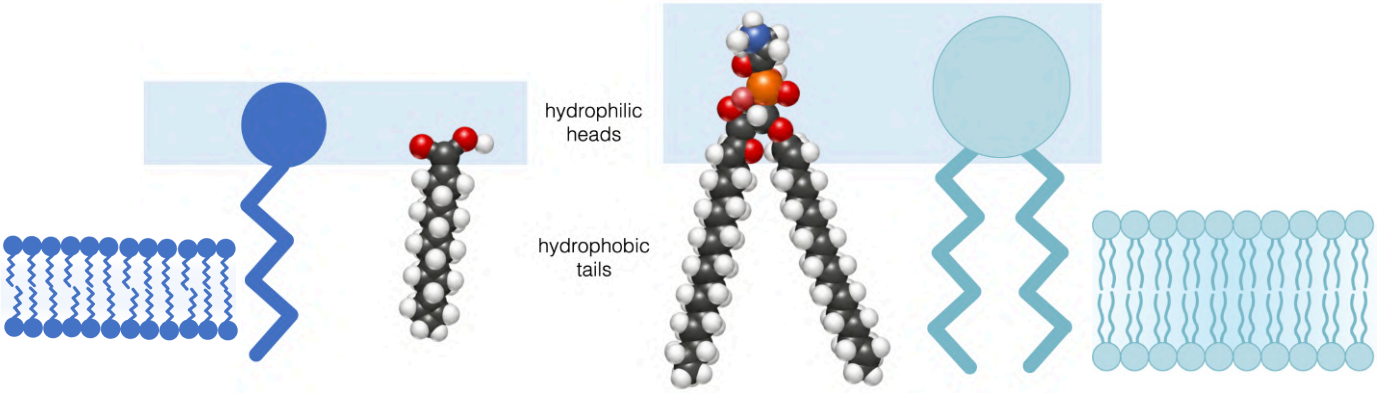
An alternative hypothesis is that carbon compounds came from comets and asteroids

Optional Extension Further challenges to abiogenesis Dr. James Tour

5HL Spontaneous Formation of Vesicles

amphipathic – molecule with polar and non-polar ends

vesicles – small droplets of fluid enclosed in a membrane

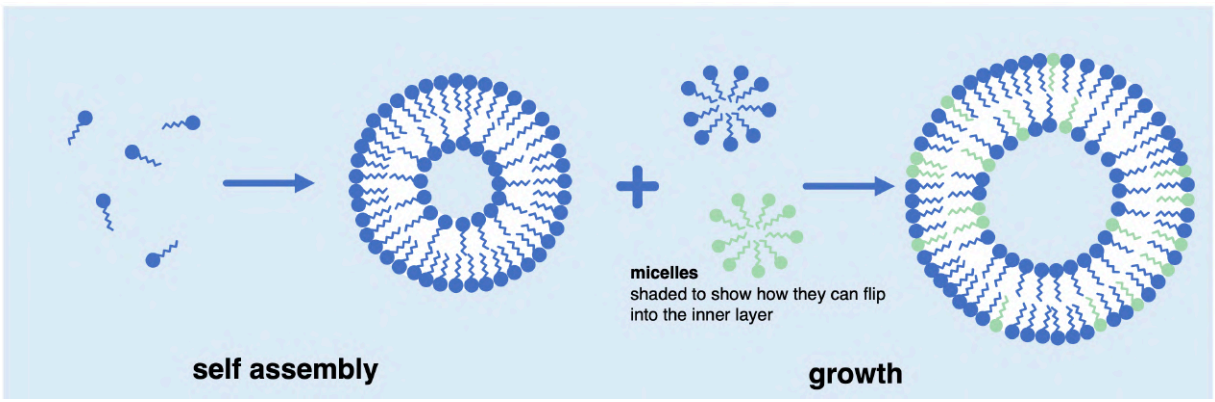


fatty acid **phospholipid**

Fatty acids may have formed the first membranes and protocells.
Later they may have become more complex phospholipids with the addition of a phosphate.

Fatty acids and phospholipids (see B1.1.12) are amphipathic.
They can spontaneously form spherical bilayers as their hydrophobic tails flip inwards and their hydrophilic heads are attracted outwards toward water.

A stable barrier forms allowing compartmentalization to occur.
Polar molecules are less able to pass across and therefore the vesicles could develop an internal chemistry that was different to the external environment.



biocode.co

Vesicles produced in the lab can:
- grow – by vesicles and micelles fusing together
- divide on their own – by vesicles splitting
- engulf particles – vesicles let particles enter

Optional Extension Challenges to membrane formation by abiogenesis.

6HL RNA as a presumed first genetic material

DNA requires enzymes to read and produce proteins encoded in the DNA molecule. However, the enzymes themselves are proteins and need to be encoded in the DNA. So how did this irreducible system arise?

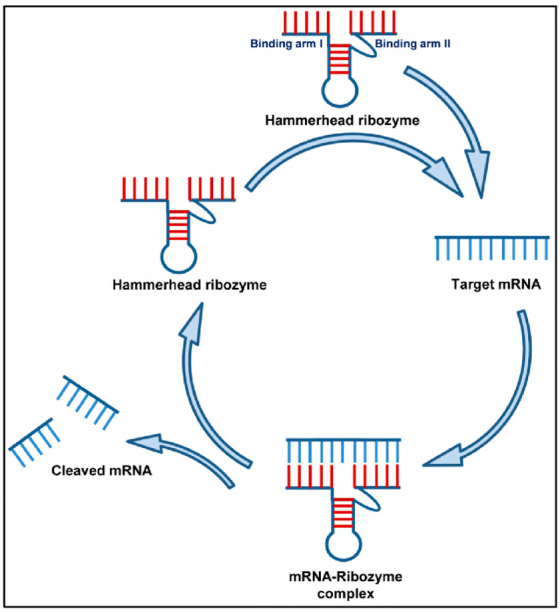
RNA World Hypothesis

The first genetic material may have been RNA as it can:

- store information
- self-replicate - with assistance in the lab
- act as an enzyme to catalyze reactions - ribozymes

Ribosomes contain some RNA which can help catalyze the formation of peptide bonds because the RNA can fold to form three dimensional shapes to make an active site.

RNA is less stable than DNA and more prone to mutations. Cells have thousands of genes that need protection from mutations to pass on their information. A cell that went on to evolve DNA would have an advantage over RNA.



hammerhead ribozyme

Optional Extension (not required for the IB exam)

Challenges to the RNA World Hypothesis by Long Story Short.

Summary of key challenges: (taken from James Tour):

- to form DNA or RNA a ribose carbohydrate is needed
  - ribose has 8 forms (isomers) - one particular form is required and it is difficult to isolate it
  - some of these reactions are time sensitive – once begun if they are not separated out, they may decompose or form a viscous mixture of polymers
  - no one knows how the ribose formed or how to join it to a nucleotide on its own
- RNA - once formed is an unstable molecule and is best stored at -80ºC
  - RNA of 189 base length, when carefully setup, can replicate on its own into an 11 to 20 base length molecule but with a high error rate. No further replication is possible after this single 'self-copying'. The RNA used in these tests was taken from living organisms.
- randomly connected nucleotides may form DNA but it will not contain information
- LUCA the last universal common ancestor would need 580 000 bases in the right order. This represents at least 206 genes.

"Scientists are clueless on the origin of life."
James Tour

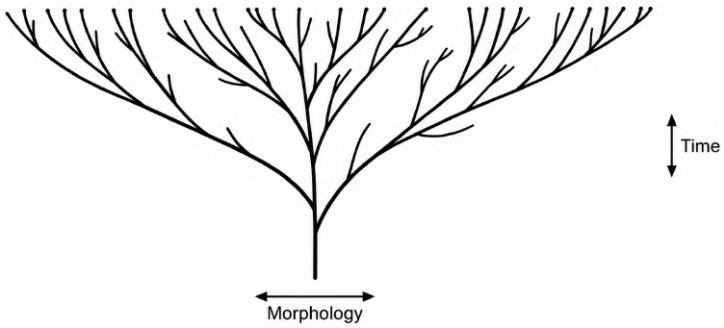
7HL Evidence for a last universal common ancestor (LUCA)

Currently cells arise from preexisting cells by cell division – binary fission, mitosis and meiosis.
Cells are complex structures and no process has been found for forming cells from simpler subunits.
All known examples of growth in tissue, an organism or a population, are a result of cell division.

Viruses are produced from simpler subunits, but they do not consist of cells, and they can only be produced inside the host cell that they infect.

The genetic code is universal.
Every species uses the same 64 codon genetic code to produce the same amino acids.
Different species also share many of the same genes and proteins.
This genetic evidence suggests all cells are related back to a last universal common ancestor (LUCA).
It is likely that other species with different codes and genes once existed but they must have become extinct when outcompeted by LUCA or species evolved from LUCA – LUCA was not the first cell.

Therefore, all cells most likely arose as the result of cell division from a single common ancestor known as the Last Universal Common Ancestor (LUCA) resulting in the tree of life model.



The origin of life on Earth stands as one of the great mysteries of science.
Steve Koppes

8HL Approaches used to estimate dates of the first living cells and LUCA

When did life first arise? The earth is believed to be 4.5 billion years old (Gya)

fossilized stromatolites:
- dated 3.5 billion years old (Gya)
- rocks formed by mats of cyanobacteria in shallow seawater
- the bacteria trapped sediments and secreted $CaCO_3$

isotopic ratios in rock:
- organic carbon from living things has a low $^{13}C/^{12}C$ ratio
- banded iron rock dated to 3.8 billion years old (Gya) has this ratio
- suggests life was present in the environment at that time
- hard zircon crystals left over from 4.1 billion year old (Gya) rock also has this ratio

genomic evidence:
- comparing the number of differences in DNA sequences can be used as a molecular clock
- earliest life forms with the least number of changes are estimated to have existed 4.5 Gya
- this is just after the Moon formed via a collision of planet Theia with the earth

9HL Evidence for the evolution of LUCA in the vicinity of hydrothermal vents

There are about 355 genes that are common to many species of bacteria and archaea – therefore they are believed to be part of the genome of a shared ancestral cell (LUCA).

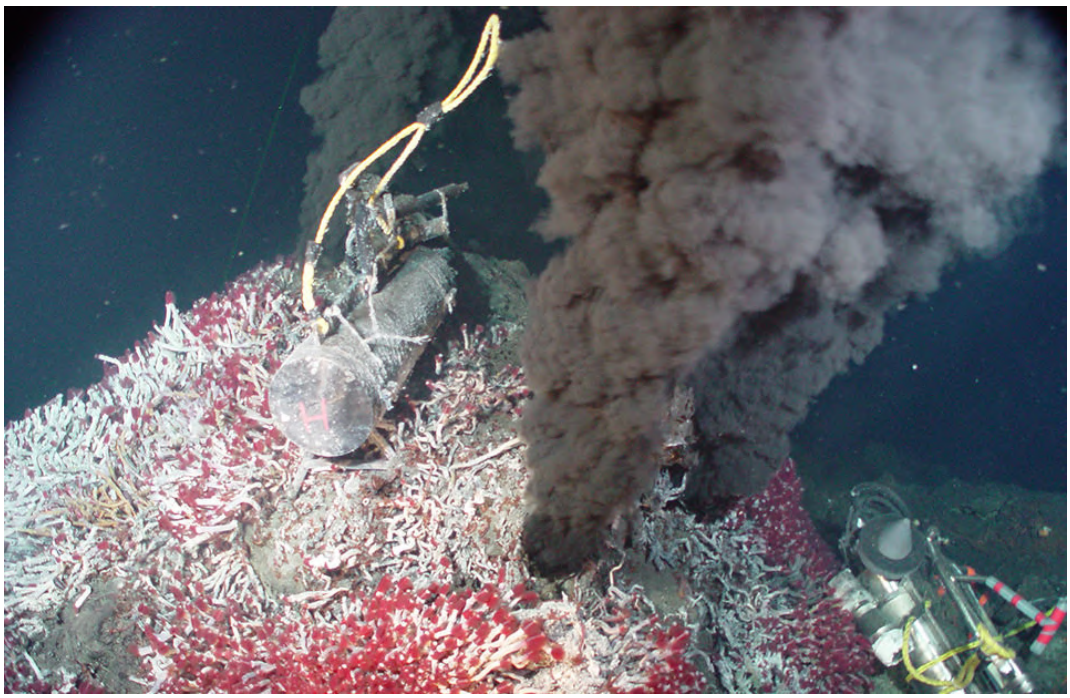
The role of these 355 genes indicate that the first cells may have been:

- anaerobic
- chemoautotrophs
  - able to gain energy from hydrogen
  - convert carbon dioxide into sugars
  - convert nitrogen into amino acids
- thermophiles - able to survive high temperatures
- carried out transcription and translation using ribosomes

The genes seem to indicate that the environment may have been high in hydrogen, carbon dioxide and iron which is similar to conditions around a hydrothermal vent.

Hydrothermal vents are the most likely location of abiogenesis:

- contain unoxidized inorganic minerals such as iron sulfide
- vary in pH
- 60-90°C
- high concentrations of hydrogen, methane, ammonia and sulfides as an energy source
- mineral precipitates
  - form a catalytic surface to speed up some chemical reactions
  - form porous structures that may have acted like early cell compartments
  - formed chemical gradients that may have provided energy to early life



NOAA

Have you entered into the springs of the sea
or walked in the recesses of the deep?
Job 38