

Origins of cells

Revision notes • How the first cells may have arisen: early Earth, Miller–Urey, fatty acid vesicles, the RNA world and evidence for LUCA near hydrothermal vents.

For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

Origins of cells **Spec A2.1** **HL only**

Early Earth and the first carbon compounds **Spec A2.1.1, A2.1.4**

Earth formed about 4.5 billion years ago. Conditions on the early Earth were very different from today, and these differences explain how the first **carbon compounds** could have formed before any life existed (pre-biotic formation).

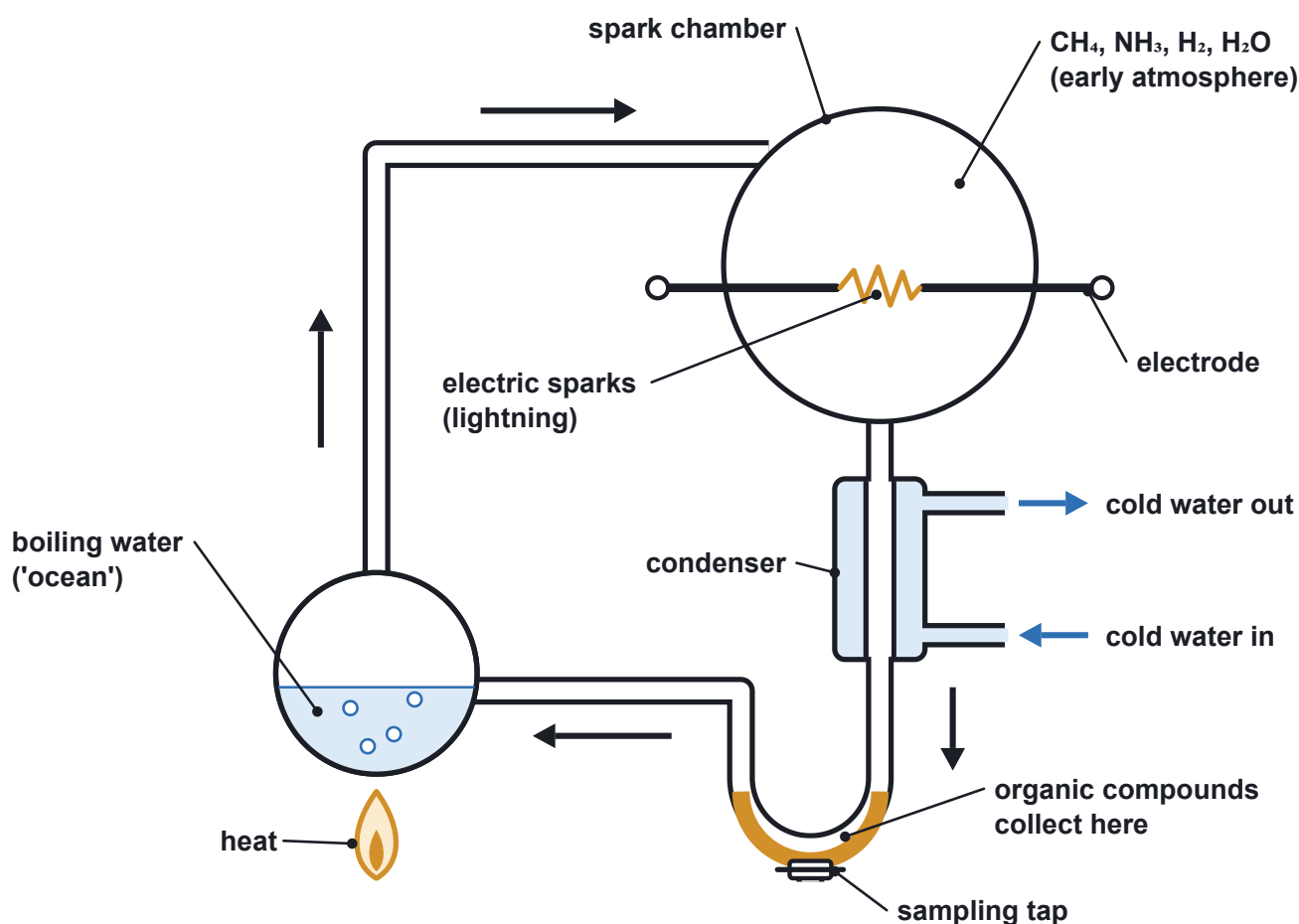
Conditions on early Earth		
Feature	Early Earth	Consequence
Free oxygen (O₂)	Little or none in the atmosphere	Newly formed carbon compounds were not broken down by oxidation
Ozone layer	Absent, because ozone (O ₃) forms from oxygen	Ultraviolet light penetrated to the surface and supplied energy for reactions
Carbon dioxide and methane	Much higher concentrations than today	Strong greenhouse effect, so higher temperatures
Other energy sources	Frequent lightning, volcanic activity and meteorite impacts	Energy to break and form chemical bonds

Under these conditions a variety of carbon compounds, such as amino acids, sugars and nucleotide bases, may have formed **spontaneously by chemical processes that do not now occur**. Today such compounds would not build up, because oxygen in the atmosphere oxidises them and living organisms quickly consume them.

Evidence: the Miller–Urey experiment

In 1952–53, Miller and Urey tested whether carbon compounds could form from inorganic molecules under conditions thought to resemble the early Earth.

1. Water was boiled in a flask to produce water vapour, representing the ocean and evaporation.
2. The vapour mixed with methane (CH₄), ammonia (NH₃) and hydrogen (H₂), representing an early atmosphere with no oxygen.
3. Electrodes produced continuous sparks in the gas mixture, simulating lightning as an energy source.
4. A condenser cooled the gases, so water and any dissolved products fell like rain into a trap and returned to the flask.
5. After about a week the liquid had turned brown. Analysis showed several amino acids, including glycine and alanine, and other carbon compounds.



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The Miller-Urey apparatus: sparks act as **lightning** in an early-atmosphere gas mixture, and the condensed products collect in the trap.

Evaluating the experiment

Evaluating the Miller-Urey experiment	
Aspect	Evaluation
Main finding	Strength: it showed that amino acids and other carbon compounds can form from inorganic molecules with no living organisms present.
Control and repeatability	Strength: the sealed, sterilised apparatus meant products could not come from contaminating organisms, and the experiment has been repeated many times. Reanalysis of stored samples in 2008 detected more than 20 amino acids.
Gas mixture	Limitation: the early atmosphere is now thought to have been less reducing, with more CO ₂ and N ₂ . Repeats using such mixtures give much smaller yields of amino acids.
Scope	Limitation: it produced monomers only. It did not show how polymers, self-replicating molecules or cells formed.
Realism	Limitation: the exact conditions on early Earth are unknown and cannot be replicated, so the model may not match them.

Amino acids have also been found in some meteorites, which supports the idea that carbon compounds can form by non-biological chemistry.

Exam tip: 'Evaluate' needs strengths and limitations and a judgement: the experiment supports the idea that carbon compounds could form spontaneously, but says nothing about how cells arose.

Living and non-living, and the challenge of the first cells Spec A2.1.2, A2.1.3

Cells are the smallest units of self-sustaining life. A single cell can take in energy and materials, carry out metabolism, keep its internal conditions stable and reproduce. Nothing smaller than a cell, such as an organelle or a molecule, can do all of these on its own.

Living things carry out all the functions of life: metabolism, nutrition, growth, response to stimuli, homeostasis, excretion, movement and reproduction. Non-living things may show one or two of these (a crystal grows, a flame uses oxygen) but not all of them together, and they have no genetic material that is inherited and evolves.

Why viruses are considered non-living

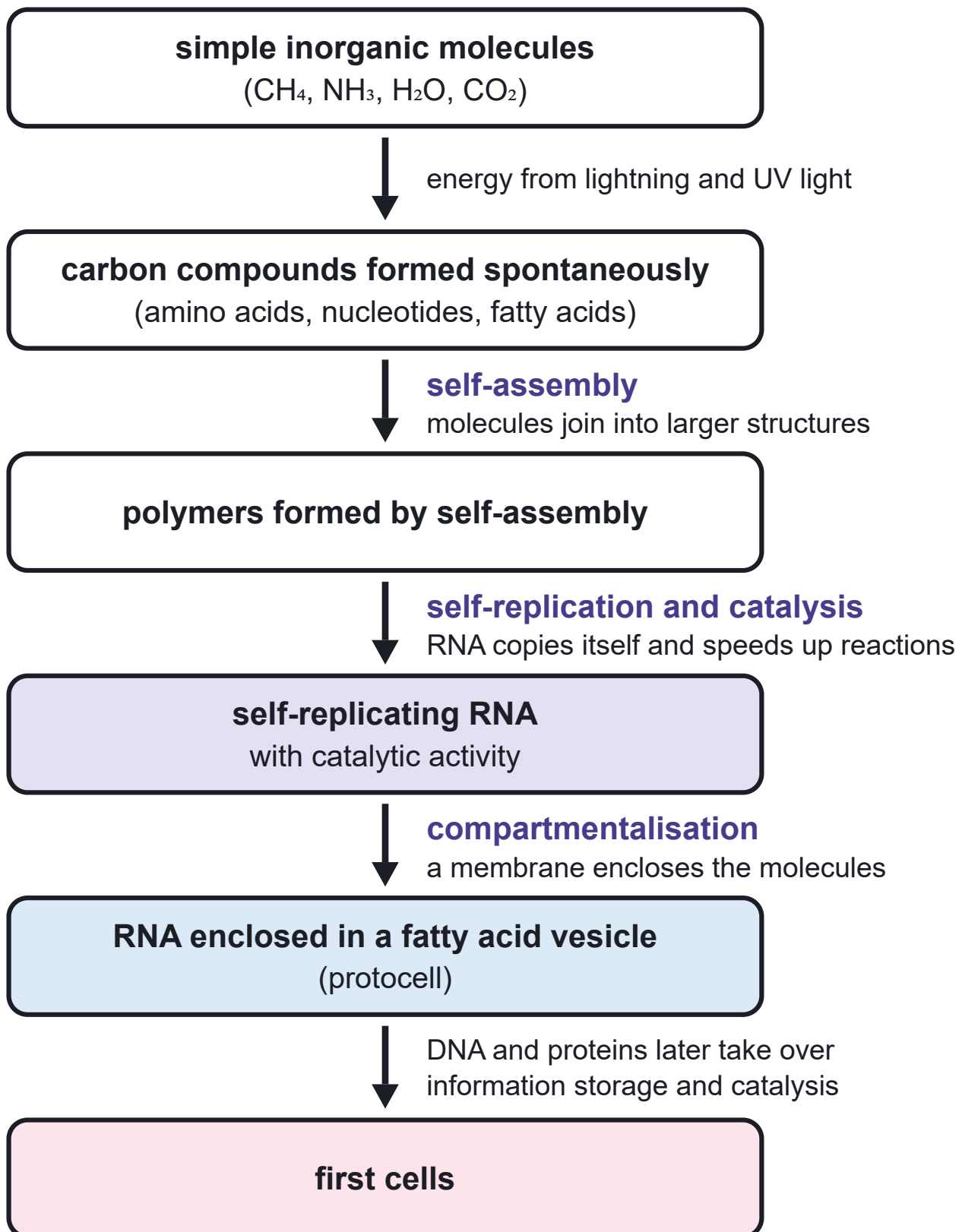
- They are not cells: they have no cytoplasm and no plasma membrane of their own.
- They have no metabolism of their own: they produce no ATP and have few or no enzymes.
- They cannot reproduce independently: they use the host cell's ribosomes, enzymes, ATP, nucleotides and amino acids to make copies of themselves.
- They do not grow, excrete or maintain homeostasis, and outside a host cell they are inert particles.

Viruses do have genetic material and evolve by natural selection, which is why their status is sometimes debated.

The challenge of explaining the origin of cells

Cells are highly complex structures that can **currently only be produced by division of pre-existing cells**. For the first cells to arise from non-living matter, several requirements had to be met.

Requirements for the evolution of the first cells	
Requirement	Why it was needed
Catalysis	Reactions had to be speeded up so molecules could be made fast enough; early catalysts may have been mineral surfaces or RNA
Self-replication of molecules	A molecule had to be copied so that information could be passed on and inherited
Self-assembly	Molecules had to join spontaneously into larger structures, such as polymers and membranes
Compartmentalisation	A membrane boundary had to enclose the molecules so internal chemistry could differ from the surroundings



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From chemicals to the first cells: each step meets one of the **requirements** for life.

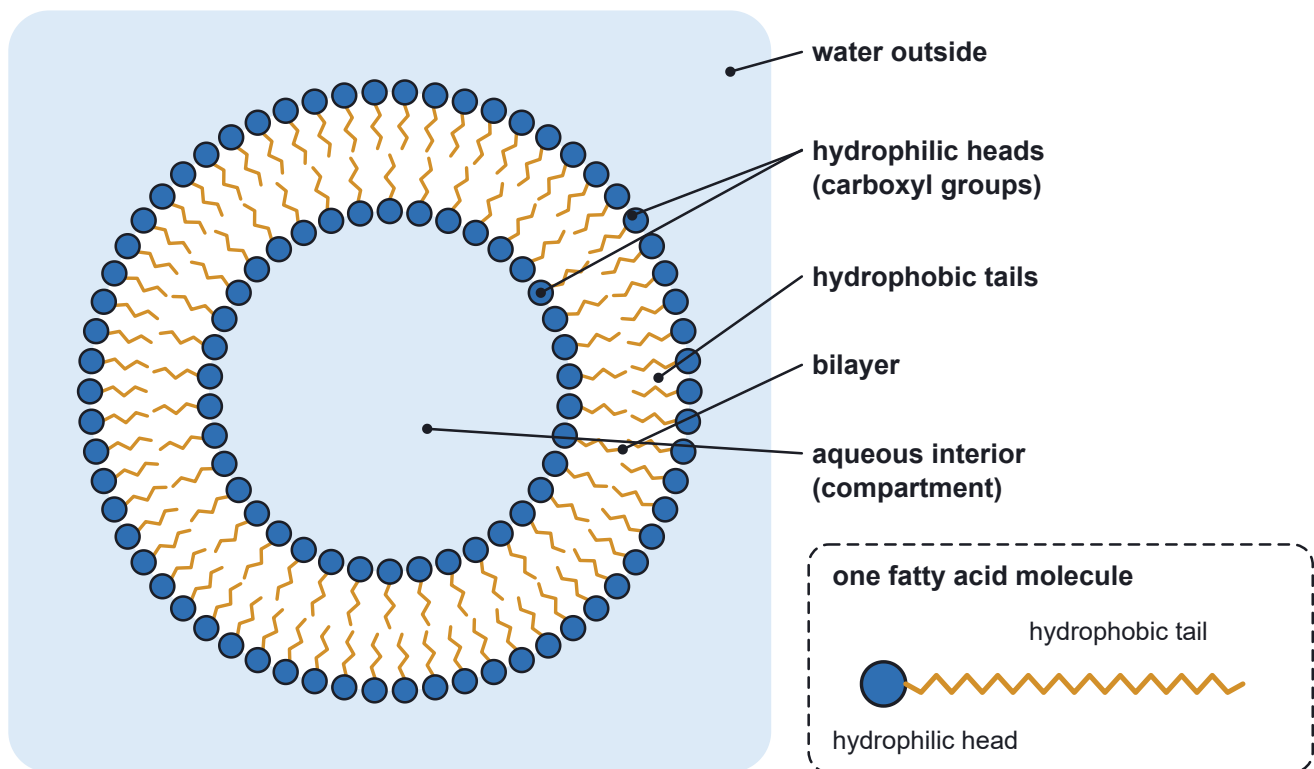
Exam tip: Nature of science: hypotheses must be testable. The exact conditions on pre-biotic Earth cannot be replicated and the first protocells did not fossilise, so hypotheses about the origin of cells are difficult to test.

Vesicles and RNA as the first genetic material Spec A2.1.5, A2.1.6

Fatty acids are **amphipathic**: each has a hydrophilic carboxyl head and a long hydrophobic hydrocarbon tail. In water they **coalesce spontaneously into spherical bilayers**, with the heads facing the water inside and outside and the tails hidden in the middle. These hollow spheres are vesicles.

No enzymes or energy input are needed: the bilayer forms because the hydrophobic tails are excluded from water, and closing into a sphere leaves no exposed edges.

- Formation of a **membrane-bound compartment** allows internal chemistry to become different from that outside the compartment.
- Molecules such as RNA can be concentrated inside, so they meet and react more often.
- Fatty acid vesicles can grow by taking in more fatty acids and can divide, a simple model of how protocells might have reproduced.



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Fatty acids coalesce into a **bilayer vesicle**, enclosing an aqueous compartment.

RNA as a presumed first genetic material

Modern cells store information in DNA and use proteins as enzymes, but each depends on the other: DNA is needed to make proteins, and proteins are needed to copy DNA. RNA can do both jobs, so it is **presumed to have been the first genetic material**, an idea called the RNA world hypothesis.

Why RNA could have been the first genetic material

Property of RNA	Why it matters
Stores information in its base sequence	It can act as genes
Can be replicated by complementary base pairing	Information can be copied and inherited
Has some catalytic activity (ribozymes)	It can act as an enzyme, possibly even helping to catalyse its own replication

Evidence: **ribozymes in the ribosome** are still used to catalyse **peptide bond formation** during protein synthesis. The catalytic site of the ribosome is made of rRNA, not protein. Later, DNA (more stable) probably took over information storage, and proteins (more varied and better catalysts) took over most catalysis.

Exam tip: Linking question: for what reasons is heredity an essential feature of living things? Self-replicating RNA gave the first heritable variation for natural selection to act on.

The last universal common ancestor Spec A2.1.7, A2.1.8, A2.1.9

The **last universal common ancestor (LUCA)** is the most recent population of organisms from which all organisms now living on Earth are descended. It was not the first cell: it already had DNA, ribosomes and a membrane.

Evidence for LUCA

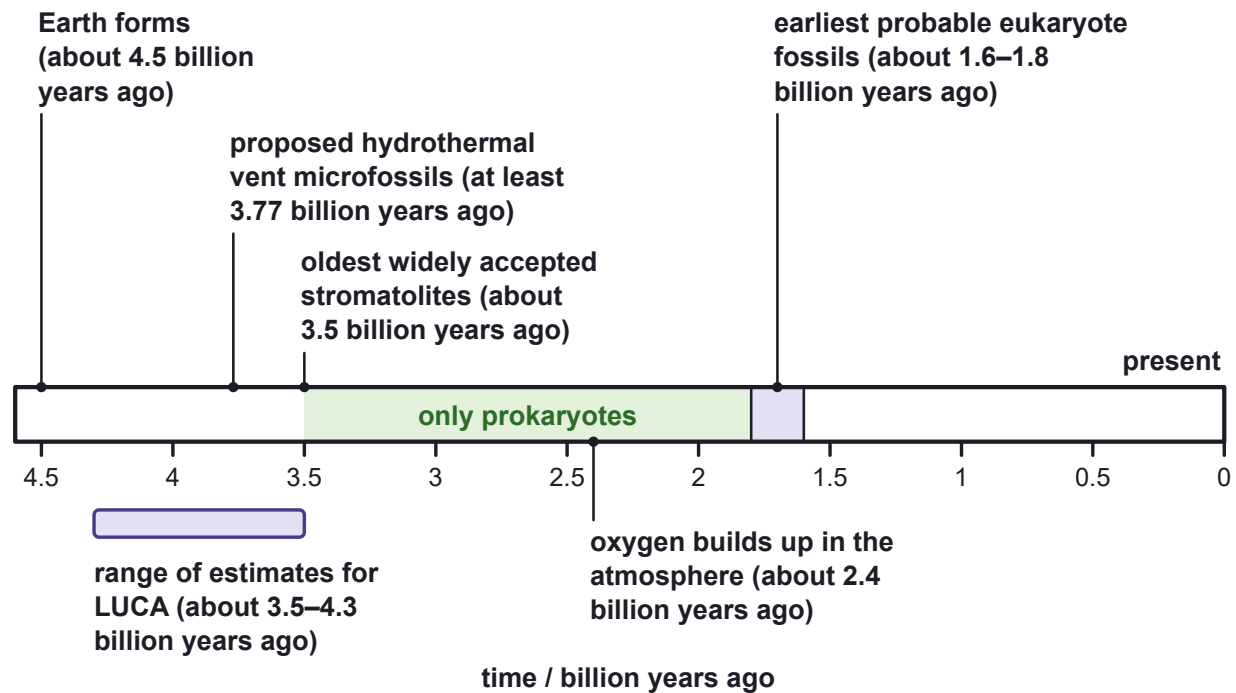
- The **universal genetic code**: almost all organisms use the same codons for the same amino acids. Such an arbitrary code is very unlikely to have evolved identically more than once.
- **Shared genes** across all organisms: genomic studies have identified several hundred genes found in both bacteria and archaea, including genes for ribosomal proteins and for DNA replication, transcription and translation.
- Shared biochemistry: all cells use DNA, ribosomes, ATP and the same 20 amino acids.

Other forms of life probably also evolved, but became extinct, most likely due to **competition from LUCA and its descendants**. This explains why all life today shares one genetic code.

Estimating the dates of the first cells and LUCA

Approaches used to estimate dates	
Approach	How it works
Fossils	Microfossils and stromatolites (layered rocks built by mats of microbes) show that cells were present; the oldest widely accepted stromatolites, from Western Australia, are about 3.4-3.5 billion years old
Radiometric dating	Radioactive isotopes in rocks decay at a known rate (fixed half-life), so the age of the rock containing a fossil is calculated from the ratio of parent isotope to decay product
Carbon isotope ratios	Organisms take up carbon-12 in preference to carbon-13, so carbon enriched in carbon-12 in ancient rocks suggests biological activity
Molecular clock	Differences in the base sequences of conserved genes build up at a roughly constant rate; calibrated with dated fossils, the number of differences estimates when lineages split, back towards LUCA

Earth is about 4.5 billion years old. Evidence for the first cells ranges from widely accepted fossils about 3.5 billion years old to disputed traces that are older: possible vent microfossils at least 3.77 billion years old and carbon enriched in carbon-12 in a 4.1-billion-year-old mineral grain. Molecular clock estimates for LUCA vary widely between studies; a 2024 study put it at about 4.2 billion years ago. Life has therefore been evolving for an **immense length of time**, roughly 4 billion years.



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Life has existed for about 4 billion years, and for roughly 2 billion years only prokaryotes were present.

Evidence that LUCA evolved near hydrothermal vents

Hydrothermal vents on the sea floor release hot, mineral-rich water. They provide energy from chemical gradients, such as dissolved hydrogen, and iron and sulfur minerals that can act as catalysts.

- Fossil evidence: tiny tubes and filaments resembling microbes have been found in ancient sea-floor hydrothermal vent precipitates in rocks from Quebec, Canada, that are at least 3.77 billion years old.
- Genomic evidence: conserved sequences traced back to LUCA include genes for living without oxygen and at high temperatures, for using hydrogen and carbon dioxide, and for many iron-sulfur proteins. These match the conditions at hydrothermal vents.

Common mistake: LUCA was not the first living cell. It was a later, already complex organism; earlier lineages existed but left no surviving descendants.

Quick check

1. Why did ultraviolet light reach the surface of early Earth?
2. Name the four requirements for the evolution of the first cells.
3. Which molecule in the ribosome catalyses peptide bond formation?
4. Give two pieces of evidence for a last universal common ancestor.

Quick check answers

Origins of cells

1. There was no free oxygen and therefore no ozone layer to absorb it.
2. Catalysis, self-replication of molecules, self-assembly and compartmentalisation.
3. rRNA, acting as a ribozyme.
4. The universal genetic code and genes shared by all organisms.