HL IB Biology

Your notes

Origins of Cells

Contents

Formation of Carbon Compounds (HL)

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Origin of Carbon Compounds

Conditions on early Earth and the origin of carbon compounds

- The conditions on early Earth were **not able to support life**, but are believed to have been instrumental in the origin of biological compounds that made life possible

- **Higher atmospheric temperatures**
  - The early atmosphere contained **higher levels of carbon dioxide and methane** than our present atmosphere
    - Methane and carbon dioxide are powerful **greenhouse gases**
    - They **trap infrared radiation** coming from the surface of the earth and prevent it from escaping into space, which in turn **increases surface temperatures**; this is called the **greenhouse effect**
  - The higher levels of carbon dioxide and methane in the early atmosphere led to the **surface temperatures of Earth being much higher** than it is today

- **UV radiation**
  - The atmosphere of early Earth **lacked free oxygen**, which wasn't only a problem for sustaining life but also **prevented ozone from forming**
    - Ozone (O_3) is formed when ultraviolet (UV) radiation from the sun interacts with oxygen molecules (O_2)
  - **Ozone absorbs damaging UV radiation** and protects life on Earth
  - This lack of free oxygen, and therefore ozone, in the early atmosphere, led to **UV radiation penetrating to the surface of Earth**
    - UV radiation cause DNA damage and increases the rate at which mutations occur; this can be harmful to living organisms

- These conditions on early Earth may have resulted in the **spontaneous formation of carbon compounds** by chemical processes that do not currently occur
  - **Adding energy**, such as heat or UV radiation, to the mixture of gases that would have been present in the early atmosphere could have led to the **formation of organic molecules** such as amino acids, simple sugars, nucleotides and fatty acids
  - These organic molecules would have formed the building blocks of early cells
  - The scientists Alexander Oparin and JBS Haldane both proposed this idea as the '**primordial soup' hypothesis** to explain the origin of biological molecules
- It is possible that the **high levels of UV radiation** on early Earth could then have catalysed the **formation of larger polymers**, such as proteins, complex sugars, mRNA and phospholipids, from these simpler molecules

The possible formation of the first organic molecules diagram

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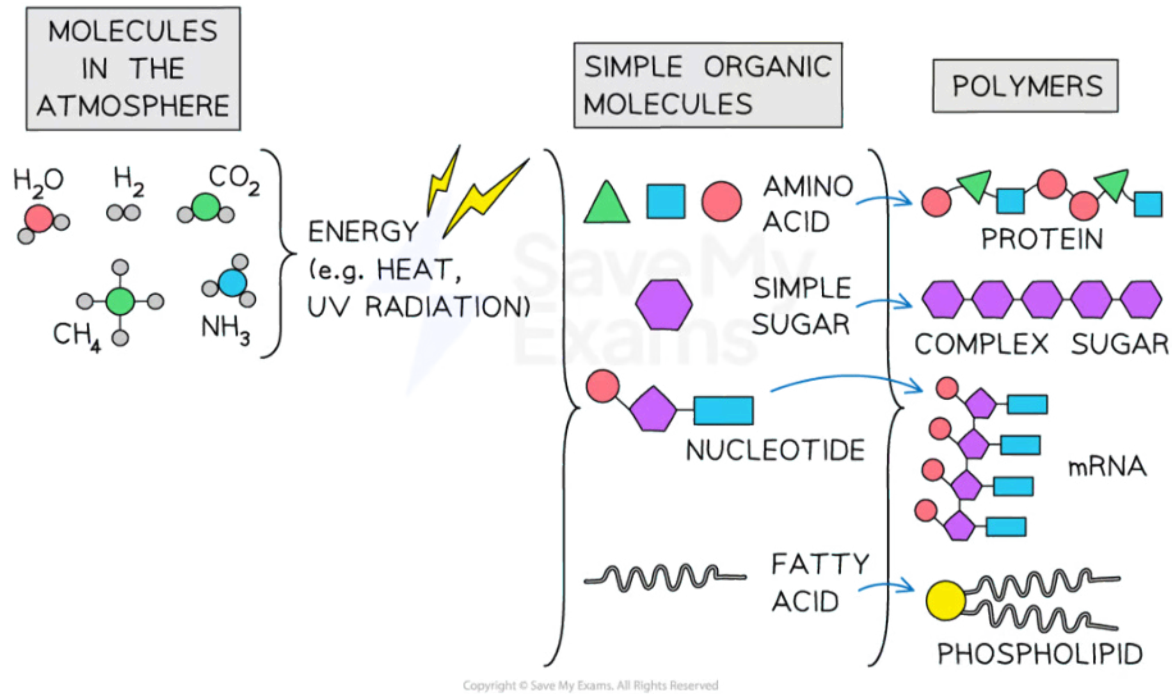


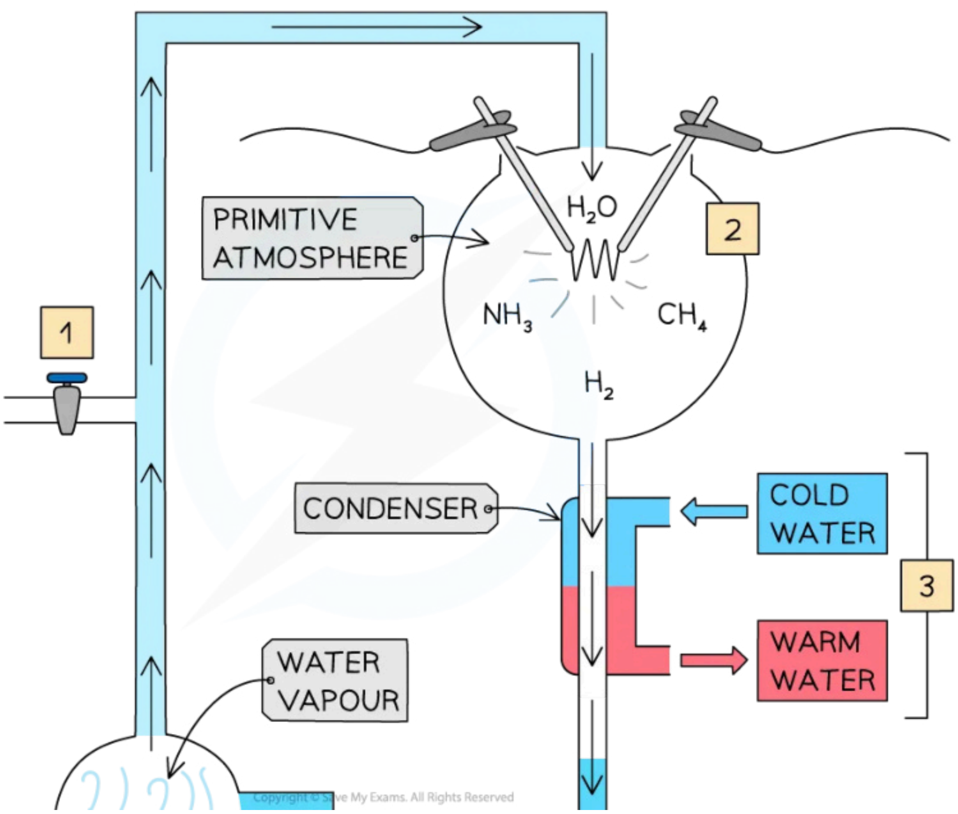
Heat and radiation could allow the synthesis of inorganic molecules into simple organic molecules which could then have assembled into polymers to provide the building blocks of life

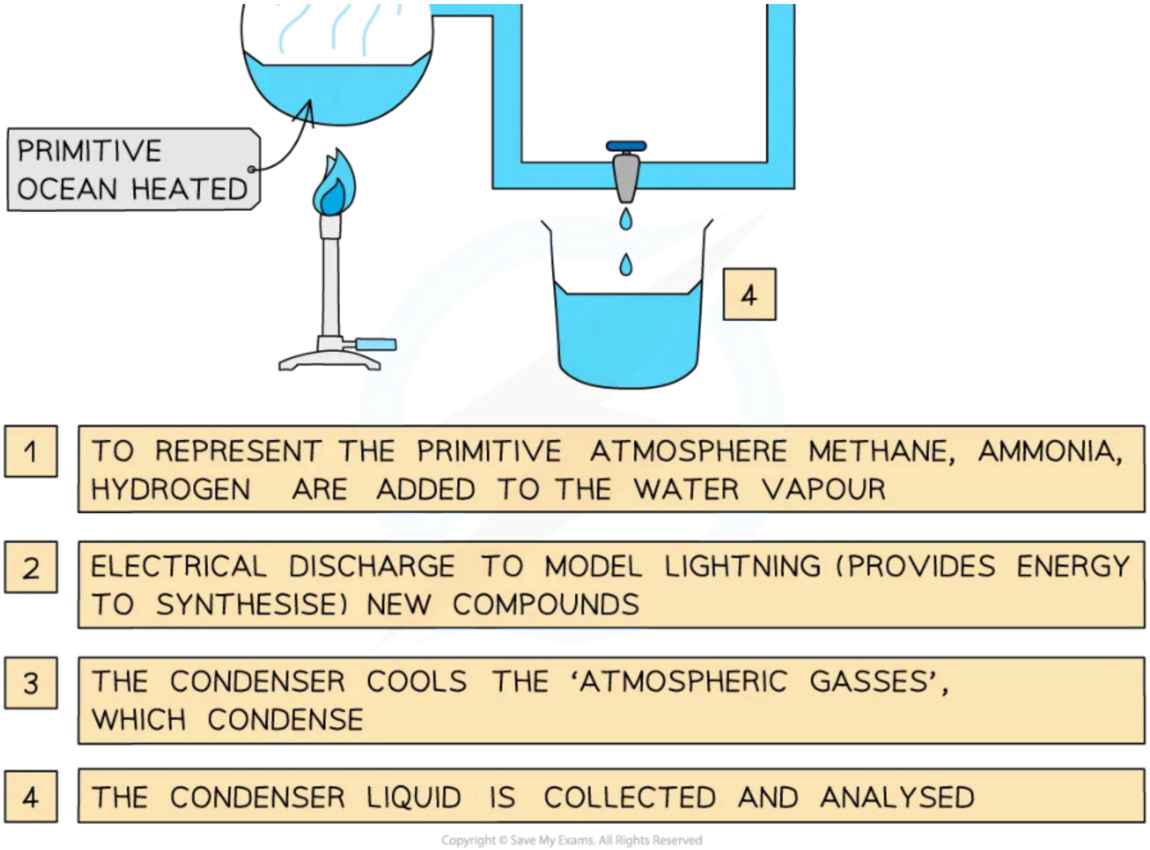
Origin of Carbon Compounds: Evidence

The Miller-Urey experiment

- The scientists Miller and Urey recreated the conditions thought to have existed on Earth prior to life using a specific piece of apparatus
- The apparatus allowed them to:
  - Boil water to produce **steam**, recreating the early primordial soup **evaporating** in the **high temperatures** that existed on Earth
  - Mix the steam with a mixture of **gases** (including methane, hydrogen and ammonia) that recreated the **atmosphere**
  - Add electrical discharges to the gases to stimulate lightning (one of the sources of energy available at the time)
  - Cool the mixture (representing the condensation of water in the atmosphere)
- After a week Miller and Urey analysed the condensed mixture and found **traces of simple organic molecules**, including amino acids

The apparatus used by Miller and Urey diagram





Miller and Urey used laboratory apparatus to simulate conditions on early Earth

Evaluating the Miller-Urey experiment

- Methane availability
  - At the time Miller and Urey performed their experiment, it was believed that they simulated the early atmosphere accurately by including **high levels of methane**
  - It is now believed however, that **methane may have been in low supply** in the atmosphere of early Earth
- The energy source
  - Miller and Urey used an **electrical discharge** as a source of energy instead of UV light
  - For the synthesis of organic molecules, however, carbon dioxide, nitrogen and water require **nuclear and UV radiation along with electrical discharges**
- The presence of water
  - In a watery environment **amino acids tend to remain as monomers** rather than joining to form proteins
  - Given that water is needed to form the 'primordial soup', this contradicts the idea that complex molecules could have formed in this environment
- Nucleotides
  - Miller and Urey were **unable to generate nucleotides** with their experiments
  - Nucleotides have since been chemically synthesised using a different approach

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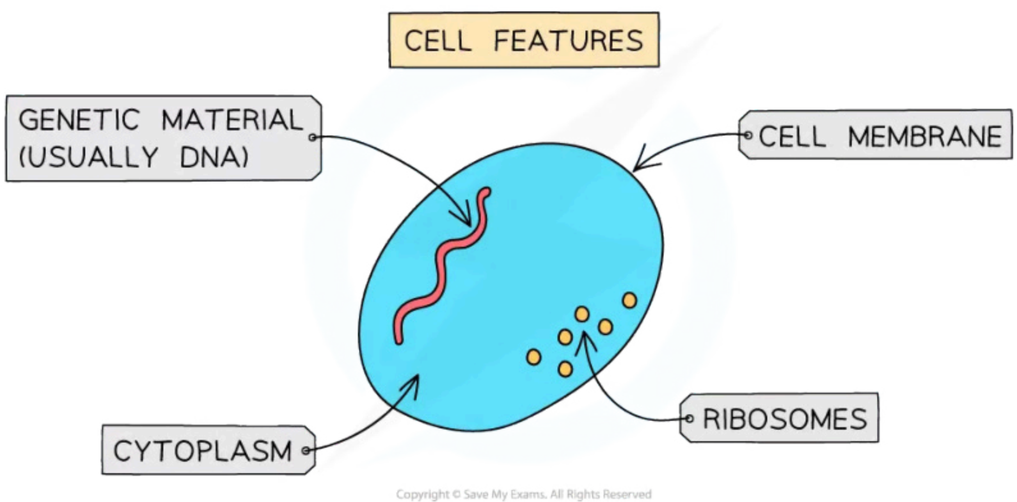
Evolution of Cells (HL)

Cells: Units of Life

Cells as the smallest units of self-sustaining life

- Cells are considered to be the **smallest units of life**
- All cells have the following features in common:
  - They are **enclosed by a plasma membrane**, or cell surface membrane, which separate the cell contents from the outside
  - They **store genetic information in DNA molecules** which is expressed during protein synthesis

Features of all cells diagram



All cells have certain features in common

- Life can be defined by the following features:
  - The occurrence of **metabolic reactions**, e.g. respiration
  - The need for **nutrition**
  - The production of metabolic waste which must be **excreted**
  - The ability to **reproduce** and to **pass genetic information on** to offspring
    - This allows for evolution by natural selection
  - The ability to **receive and respond to stimuli** from the **external** and **internal environments**
  - The ability to **grow**
- **Viruses** are considered to be **non-living**
  - They **lack a cell structure and organelles** and are therefore unable to perform most of the characteristics of life, e.g.
    - They do not carry out metabolic reactions
    - They do not require nutrition

- They are also **unable to replicate independently** and must rely on the cellular components of the host cells that they infect

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The First Cells

Explaining the spontaneous origin of cells

- Cells are considered to be **complex structures** that can only form from the **division of pre-existing cells**
- The question is, how did the first cells come into existence if there were no pre-existing cells to divide?
- We know that all cells:
  - Are surrounded by a **partially permeable membrane**
  - Contain **genetic material** that can be **passed on to new cells**
  - Are **capable of metabolic processes** to release energy which enables growth, maintenance and reproduction
- Assuming that the first cells did not arrive on Earth from somewhere else, they must have **originated from the non-living components** that made up the primordial atmosphere at the time
- This would have required the following steps:
  - **Simple organic compounds** needed to be synthesised from **inorganic molecules**
    - A possible mechanism for this process was demonstrated by **Stanley Miller** and **Harold Urey**
  - Simple organic compounds needed to be **assembled** into **polymers**
  - Some of these polymers needed to develop the ability to **self-replicate**
  - **Membranes** needed to surround the polymers, creating **compartments** with an internal chemistry different from the surroundings

Key stages involved in life arising from non-living components diagram

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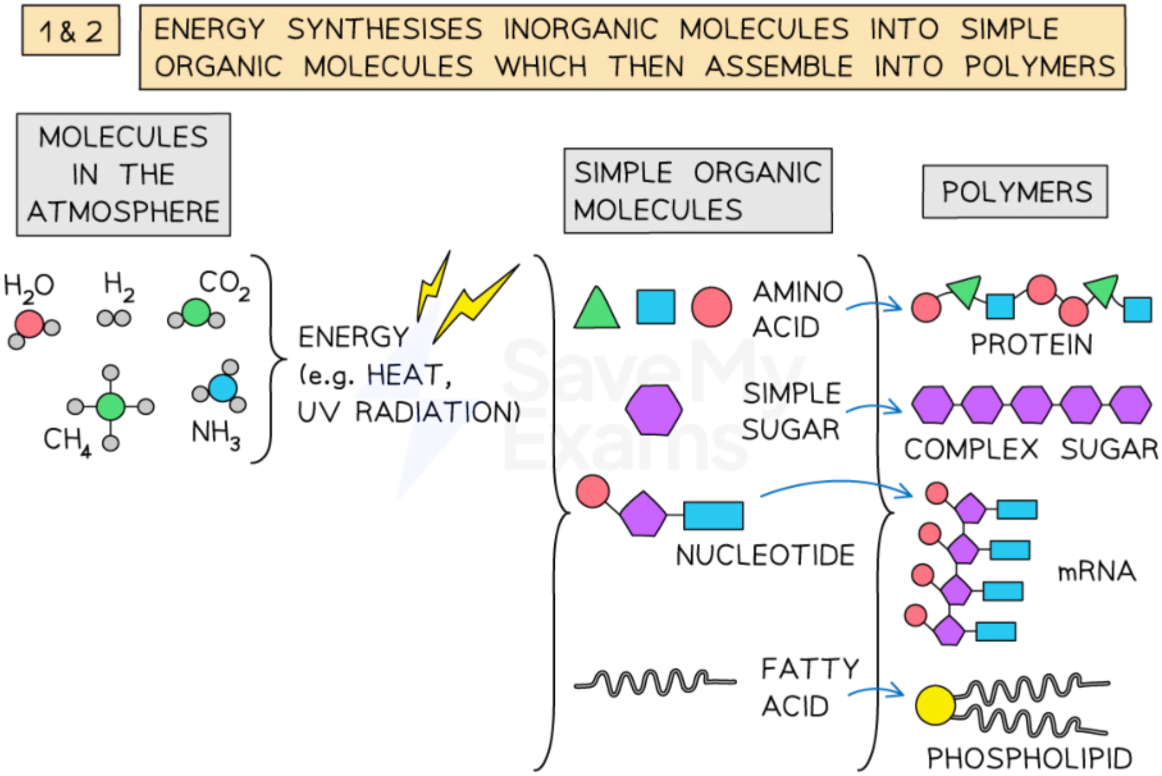
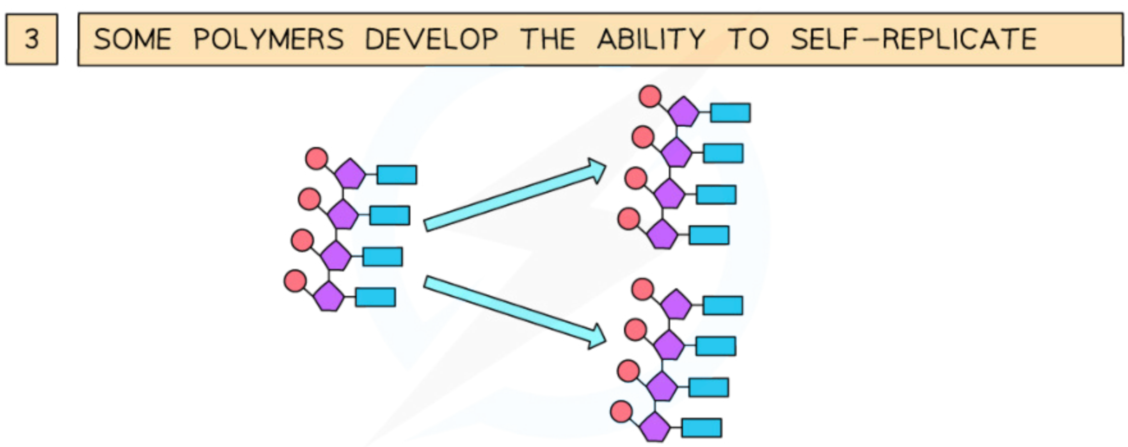

1 & 2
ENERGY SYNTHESISES INORGANIC MOLECULES INTO SIMPLE ORGANIC MOLECULES WHICH THEN ASSEMBLE INTO POLYMERS
MOLECULES IN THE ATMOSPHERE
H2O
H2
CO2
CH4
NH3
ENERGY (e.g. HEAT, UV RADIATION)
SIMPLE ORGANIC MOLECULES
AMINO ACID
SIMPLE SUGAR
NUCLEOTIDE
FATTY ACID
POLYMERS
PROTEIN
COMPLEX SUGAR
mRNA
PHOSPHOLIPID


3
SOME POLYMERS DEVELOP THE ABILITY TO SELF-REPLICATE

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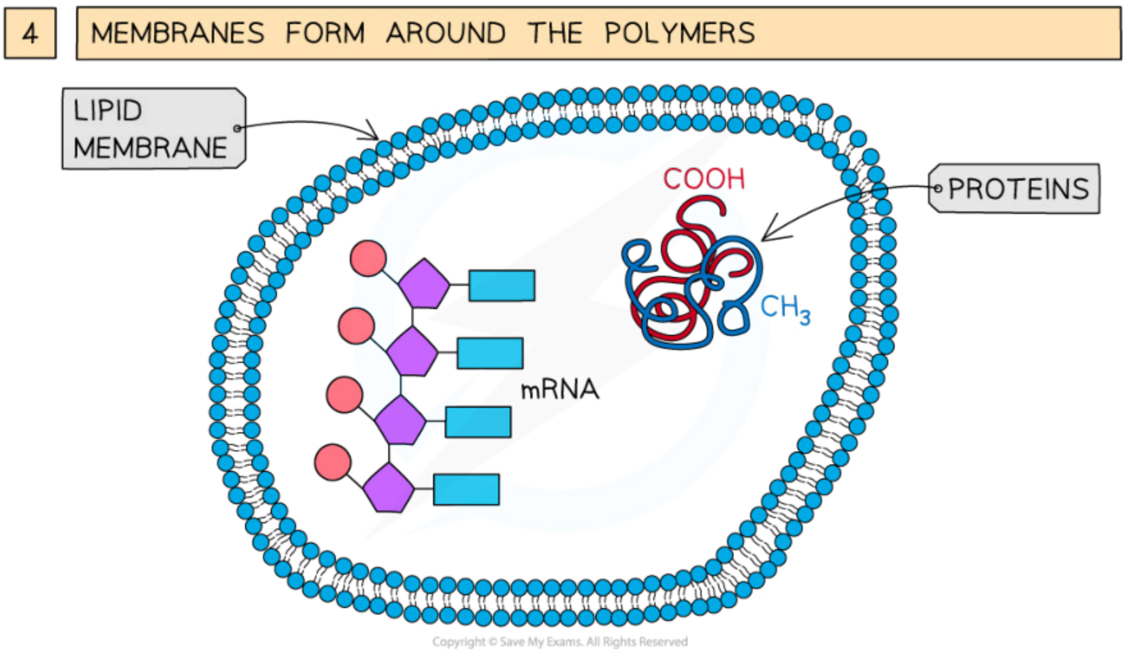

The key stages involved in life arising from non-living materials

Several theories exist that aim to explain the possible origin of cells:

Protocell-first theory

- This theory proposes that a **cell-like compartment** capable of some basic metabolic functions arose spontaneously
- These are called **protocells**
- Initially they would have **lacked genetic material**, but they would have been able to **grow**, **as well as divide** into daughter "cells"
- Eventually these protocells would have **acquired genetic material** (most likely **RNA** at first) as they evolved

Gene-first theory

- This theory starts with the spontaneous development of a **nucleic acid** (most likely **RNA**) that had the **ability to replicate** itself
- **Evolution by natural selection** would have resulted in genetic variants that could have developed a cell membrane and basic metabolic processes

Metabolism-first theory

- This theory proposes that life originated as a **system of chemical reactions** capable of sustaining itself
- The system would **eventually evolve to form cells** and genetic material
- This theory is favoured by many scientists as **most life processes** essential for the existence of cells **require energy** released by metabolic reactions

NOS: Hypotheses and theories in science should be testable; the problem of testing the theories on the origin of cells

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- The origin of cells and how they evolved remain a highly debated topic in the scientific world
- One of the cornerstones of the scientific method is **formulating hypotheses and theories that are testable**
- In the case of the theories on the origin of cells, scientists must carry out experiments testing the **underlying mechanisms** upon which the theories are based
  - This would include replicating conditions that might have been present on early Earth in a laboratory
- This presents a problem however, since it is **not possible to replicate the conditions on early Earth exactly** as they might have been
- It is also impossible to know what the exact nature of the first cells were, since **none of these early cells fossilised**
- This makes it difficult to test the hypotheses that underpin the theories about the origin of life

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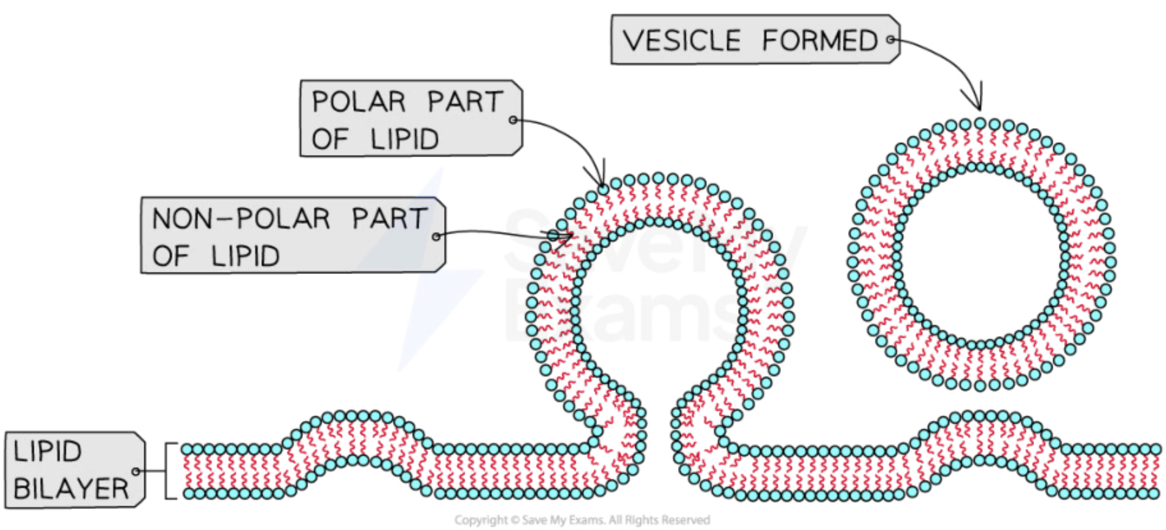
Formation of Vesicles

The spontaneous formation of vesicles

- Membranes play an important role in cells because they **separate** the genetic material and biochemical processes inside the cell from its outside environment; this is known as **compartmentalisation**
  - **Membrane formation** would have been a crucial step in the origin of cells
- It is likely that the membranes of the first cells were composed of **fatty acids** because of the amphipathic nature of these molecules
  - Fatty acids are major components of **lipids**
- When a few lipid molecules are placed in water, they will naturally form a **monolayer** on the surface; the polar parts of the lipid will be in water, while the non-polar parts will stick out of the water surface
- If more lipid molecules are added, they form **bilayers** with the polar parts facing outward towards the water environment while the non-polar parts will point towards each other
- These bilayers will **spontaneously form microspheres,** or **small vesicles**, which could possibly have formed the **membranes** of early cells

The formation of vesicles diagram



It is possible that the coalescence of fatty acids formed spherical lipid bilayers that surrounded the first cells

- These early membranes would have **separated the internal chemistry** of the cells from their outside environment
  - It is theorised that the fatty acids could have combined with **glycerol** during **condensation reactions** to form **triglycerides** as membranes evolved
  - Finally, these **triglycerides could have undergone phosphorylation** to form simple **phospholipids** which make up the main component of modern cell membranes
- Eukaryotic cells evolved to contain **multiple internal compartments**, allowing further division of activity within cells

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The First Cells: RNA

RNA as a presumed first genetic material

- For early life to evolve, the following had to emerge:
  - A system capable of **replicating itself**
  - An ability to **catalyse chemical reactions**
- In **modern cells**, these functions are carried out by **DNA** and **enzymes**, but neither of these would have been present in the pre-biotic world
- Scientists believe that **RNA may have performed both of these functions in early cells**, since it can store genetic information as well as having enzymatic properties; this is known as the **RNA world hypothesis**
  - As life evolved, DNA took over the role of **genetic storage molecule**, while proteins (enzymes) became **biological catalysts** of chemical reactions
- Properties of RNA that provides evidence for this include
  - RNA can assemble sponateously from nucleotides
  - RNA is able to replicate itself
  - RNA can control the rate of chemical reactions; modern cells contain ribozymes that catalyse the formation of peptide bonds
- Evidence that RNA may have been around before DNA includes
  - **Ribose** can be formed from methanal, **one of the main products** of the Miller-Urey experiment
  - **Deoxyribose** in DNA is **produced from ribose** in an enzyme catalysed reaction
  - Ribozymes are able to **join amino acids together** to form proteins **from an RNA template**

Examiner Tip

Remember that catalysis, self-replication of molecules, self-assembly and the compartmentalisation of different cell parts were all necessary for the evolution of early cells

Evidence for Evolution of Life (HL)

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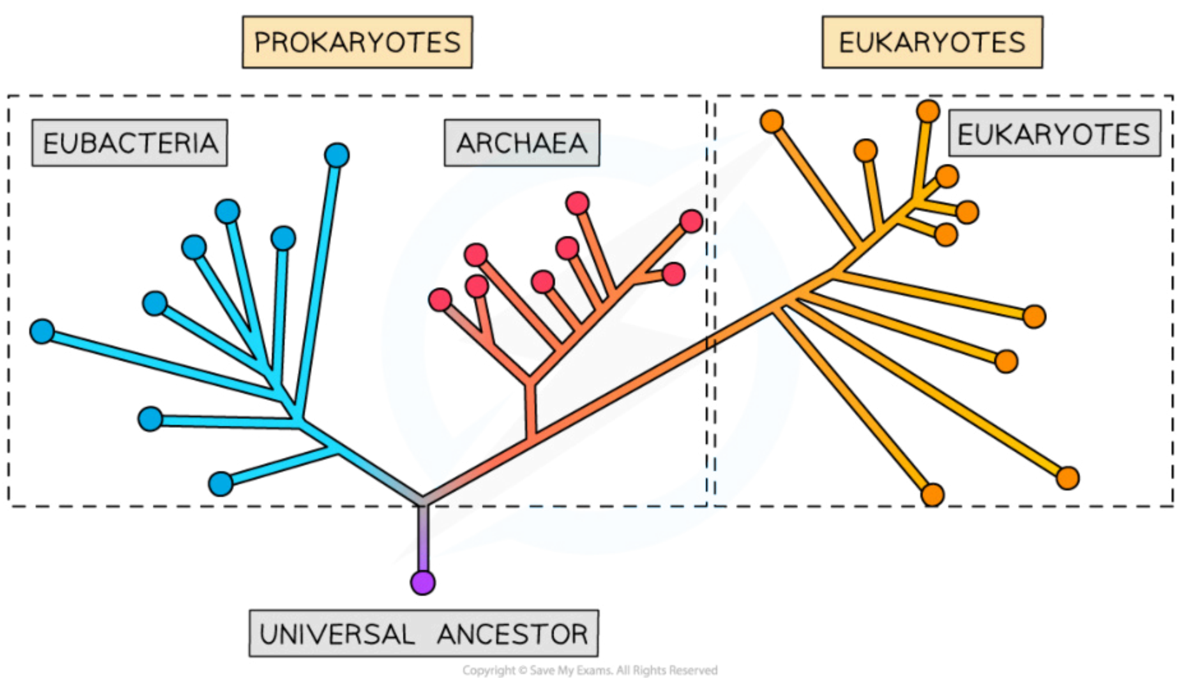
The Last Universal Common Ancestor

Evidence for a last universal common ancestor

- During the evolution of life, evidence suggests that different species have evolved from a common ancestor
  - These species will **share some similar characteristics** with their common ancestor
  - For example, the **bone structure of the vertebrate forelimb** is similar in all species of vertebrates which indicates that they inherited this structure from a common ancestor
- **DNA provides a useful tool** to determine the evolutionary relationships between species
  - Organisms with **similar DNA sequences are more closely related** than those with very different DNA sequences
- All life on Earth is thought to have evolved from an ancient common ancestor, believed to have existed about 4 billion years ago
- This organism is known as the "**L**ast **U**niversal **C**ommon **A**ncestor", or **LUCA**
  - In a phylogenetic tree of life, **LUCA** would be the organism at the very **base of the tree**

The phylogenetic tree of life diagram



The evolutionary tree of life, indicating the evolution of life from the last universal common ancestor (shown in purple)

- Evidence for a **common ancestry** shared by all living organisms include:

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- Same **biochemistry** in all organisms
- Same **DNA bases and genetic code** shared by organisms
- Same shared **amino acids** forming protein molecules in organisms
- Researchers found **several genes that are shared by eubacteria and archaea**, indicating that these genes were inherited from LUCA
- It is possible that **other organisms** may have evolved at the same time as LUCA, but **became extinct due to competition for shared resources**
- The **descendants of LUCA would have outcompeted other species** and gone on to shape the tree of life as we know it

Evolution of Life: Timescale

Estimating the timescale for the origin of life

- **Fossils** can provide evidence about the **history of life on Earth** and are often used to determine the **timescale** across which evolutionary events have occurred
- These timescales can be established using **techniques to date the fossils or the rocks** in which they are found
  - **Carbon dating** of the isotope carbon-14 for samples up to approx. 60 000 years old
  - **Radiometric dating**
    - It measures the **relative proportions of certain radioactive substances** (such as carbon-13 to carbon-12) in a sample
- **Older rocks** would be expected to contain evidence of **more ancient forms of life**, so accurately dating these would indicate when life may have originated
- Another technique by which the age of an organism can be determined is by **analysing its genome**
  - DNA changes as **mutations occur and accumulate** over time
  - By estimating the **average time for DNA mutations to occur**, the relative date when species branched from a common ancestor can be determined based on the number of mutations that have occurred between them
    - This would also apply to **changes in the amino acid composition of proteins** since any changes in the DNA will translate into a different protein structure and composition
  - On the assumption that these changes occur at a **constant rate**, this forms the basis of a **molecular clock**
  - This molecular clock can be used to determine the **date of when life on Earth originated**

Examiner Tip

Keep in mind that the timescale across which life has been evolving on Earth is immense, and that some of the numbers provided by fossil evidence, and particularly the molecular clock, are **estimates** and not exact dates.

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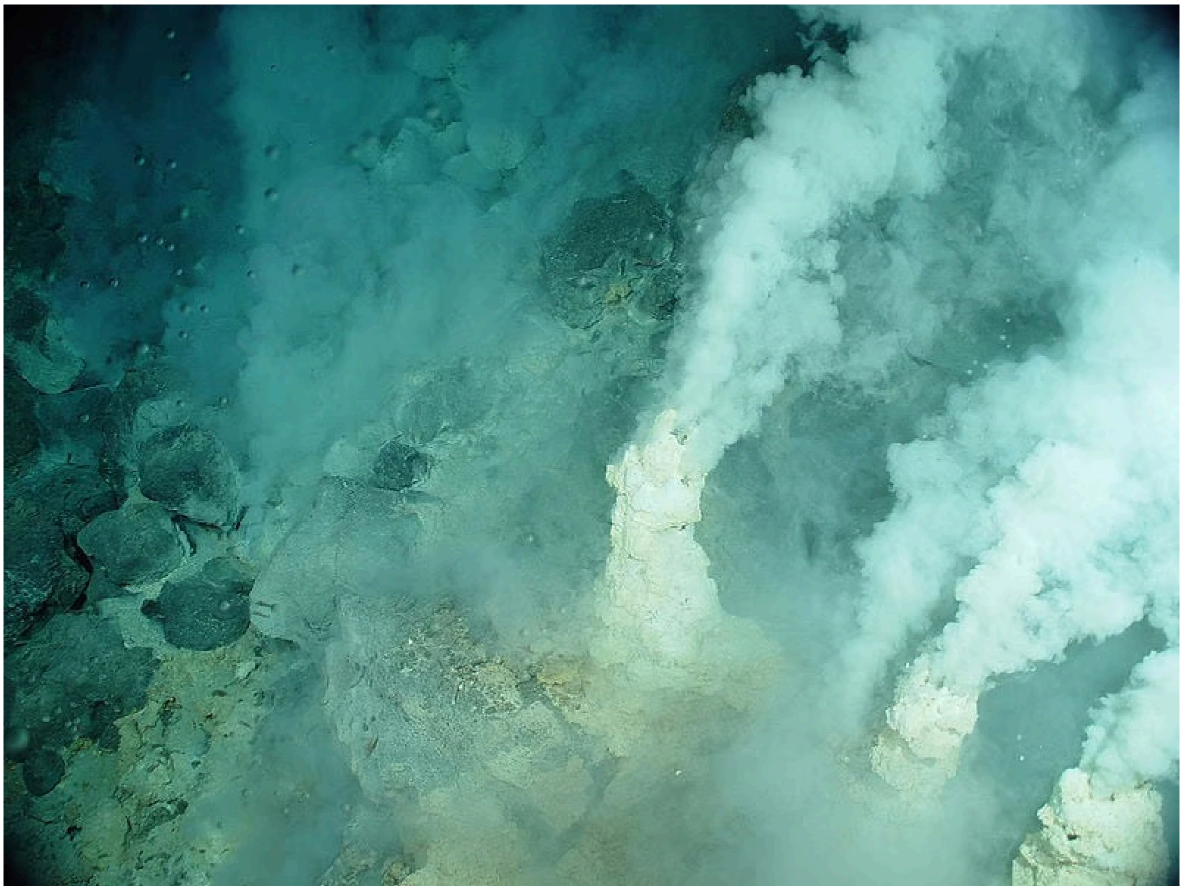
Evolution of Life: Hydrothermal Vents

Evidence for the evolution of LUCA near hydrothermal vents

- It is possible that **LUCA evolved in hydrothermal vents** deep in the ocean
- The conditions near hydrothermal vents provide opportunities for organisms to generate energy by chemosynthesis



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Life is believed to have originated near hydrothermal vents

- Scientists have found **fossilised structures in the sedimentary rocks** near deep-sea hydrothermal vents in Quebec, Canada
  - These structures are **similar to those produced by modern prokaryotes** found near hydrothermal vents
  - The fossils are **at least 3.77 billion years old**, but could be more than 4 billion years old; one of the **oldest forms of life** ever found
  - These fossil structures are **small tubes made of haematite**, which is the mineral form of iron(III) oxide

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    - The presence of carbonate and other carbonaceous material in the sedimentary rocks indicates that **oxidation and other biological activities** may have occurred there
    - It indicates that these ancient bacteria had a **similar biochemistry to modern iron-oxidising bacterial communities** that live near hydrothermal vents
- Analysis of sequence data from modern species that live near hydrothermal vents indicates that they **all share a common ancestor**
  - Based on the properties and functions amino acid sequence data from these organisms, LUCA may have had the following characteristics:
    - **Anaerobic**, therefore able to survive in the absence of oxygen
    - Converted **carbon dioxide into glucose**
    - Used **hydrogen as an energy source**, instead of sunlight
    - Converted **nitrogen into ammonia** for the synthesis of amino acids
    - Survived in environments of very high temperature (**thermophilic**)
- Fossil evidence and genetic analysis indicates that LUCA may have been an autotrophic **extremophile** that **lived in hydrothermal vents**, in an environment with an abundance of **hydrogen**, **carbon dioxide** and **iron**
- Note that this is **not the only hypothesis** for the origin of life; scientists will continue to gather and an analyse data that may support or refute existing theories