LIFE ON EARTH

Evidence for the origin of life

Analysis of the oldest sedimentary rocks provides evidence for the origin of life

1.1 Origin of organic molecules on early Earth

- ***identify the relationship between the conditions on early Earth and the origin of organic molecules***

The age of the Earth

The approximate age of the Earth, based on geological, magnetic, radiographic and palaeontological studies, is 4.5 billion years. During the **Hadean eon** (approximately 4.5 to 3.8 billion years ago) was the formation of the Earth as it was transformed from a gaseous cloud into a solid body. The heavier molten iron sank down to become the core, while the lighter rock rose to the surface, becoming the crust. As a result of the high temperatures at the centre of the Earth and due to volcanic activity, there was an emission of gases, or **outgassing**, of volatile molecules such as water (H_2O), methane (CH_4), ammonia (NH_3), hydrogen (H_2), nitrogen (N_2), and carbon dioxide (CO_2). The atmosphere was **anoxic** meaning it had no free oxygen (O_2), as all oxygen was bound within compounds such as water and carbon dioxide. This meant that there was no ozone (O_3) layer, exposing the Earth's surface to ultraviolet radiation. Most of the hydrogen gas escaped into space, as happens today, whereas the other gases accumulated and remained in the atmosphere.

Forming the first organic molecules

Early Earth, with an atmosphere of water vapour, hydrogen, methane and ammonia, provided an environment in which the production of **organic** carbon-containing molecules would be fairly easy. The energy for driving these reactions could have come from a number of sources, in particular the sun. Ultraviolet light would easily have reached the Earth's surface because no ozone layer existed. Other possible energy sources could have been lightning, hot springs and volcanoes, radioactivity in the crust, and impact from meteorites. At this stage, organic molecules would have most likely formed in the lower atmosphere or the Earth's surface. The stages of change thought to have occurred in early Earth are listed below:

- Dense clouds formed in the steamy atmosphere. These clouds were formed of water from meteorites and hydrated minerals. These clouds then formed a reflective shield from the sun's penetrating heat.
- Eventually, **meteorite** impacts declined (approximately 500 million years later) due to the protective layer

of the atmosphere and the friction caused on entry, the Earth cooled and the temperature fell below 1000°C, forming a stable rocky crust.

- The release of gases from volcanoes in turn increased air pressure in the atmosphere. When the temperatures cooled, this assisted in causing the immense clouds of water vapour to condense into liquid and fall as rain.
- Rain would have washed organic molecules into lakes and ponds rich in dissolved minerals and created an environment for reactions to occur producing new organic molecules. In turn this would have created an environment for further reactions forming other molecules and compounds and so on (see Table 1.1).
- Carbon dioxide dissolves readily in water to form carbonic acid (H_2CO_3). It would have been flushed out of the atmosphere by the rain and into the oceans where it reacted with calcium to form calcium carbonate ($CaCO_3$).
- At first, the rain evaporated as it fell on the hot rock surface but the evaporation gradually cooled the crust until the water could accumulate in the lower regions of the Earth's surface forming oceans. The first rivers were created on the continents where the water, dissolving and transporting minerals along the way, eventually ran back into the oceans.
- The dissipation of heat into space cooled the Earth, causing crust fragments to become numerous enough to form a first thin, solid cover.
- Over the next 3.5 billion years, the amount of carbon dioxide in the atmosphere was reduced as it became incorporated in rocks (e.g. limestone). The main gas remaining in the Earth's atmosphere was nitrogen. The composition of Earth's atmosphere today is somewhat different to that proposed on early Earth: 78.1 per cent nitrogen, 20.9 per cent oxygen, and 1 per cent consisting of small traces of different gases such as carbon dioxide, water vapour, methane, hydrogen and ozone.

There is much known about the composition and conditions of early Earth; however, there are a lot of questions remaining unanswered. Scientists continue to search for more evidence reflecting the conditions of early Earth that may have existed when life began. If these conditions are known then we may perhaps discover more about the building blocks from which life began.

Table 1.1

Bioelements	Biomolecules
Water: hydrogen (H), oxygen (O)	Monosaccharides (e.g. glucose), polysaccharides (e.g. starch), glycoproteins and proteoglycans
Organic: hydrogen (H), carbon (C), nitrogen (N), oxygen (O), phosphorus (P), sulfur (S)	Triacyglycerols (e.g. animal fat, seed reserves), phospholipids, glycolipids, polyisoprenoids
Ionic: sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), chlorine (Cl)	Amino acids (20) Proteins, glycoproteins and proteoglycans Nitrogenous bases (4); ribose or deoxyribose phosphate Nucleic acids (RNA and DNA)

1.2 Implications of the existence of organic molecules

■ ***discuss the implications of the existence of organic molecules in the cosmos for the origin of life on Earth***

There is very little evidence towards the existence of organic molecules in the universe or **cosmos**. The finding of the 100 kg Murchison meteorite in Victoria, Australia in 1969 was significant in providing evidence that organic molecules from outside of Earth are similar to those we have today. Nineteen of the 92 amino acids identified in the meteorite were found on Earth. This suggests that the source of organic molecules needed for the origin of life on Earth may in fact have originated from outside of the Earth. Theories presented by Haldane and Oparin (1923) did not provide much evidence for the existence of organic molecules until the supporting experiments of Urey and Miller (1953). Urey and Miller created the conditions thought to be those of early Earth and these conditions resulted in the change from **inorganic** molecules to organic molecules. Although this theory is commonly supported, there is no evidence to support the mechanism for complex organic compounds changing to early life forms. The question still remains unanswered and quite controversial.

1.3 Evolution of chemicals of life: theories and their significance to the origin of life

■ ***describe two scientific theories relating to the evolution of the chemicals of life and discuss their significance in understanding the origin of life***

The major theories accounting for the origin of life on Earth are:

- steady state—life has no origin
- spontaneous generation—life arose from non-living matter on numerous occasions
- special creation—life was created by a god or supernatural event at a particular time
- cosmozoan/panspermia—life arrived on Earth from elsewhere
- biochemical evolution or chemosynthetic theory—organic compounds are produced from inorganic molecules, leading to early life forms.

Steady state theory

This theory suggests that the Earth and its species had no origin; they always existed. The Earth has always been able to support life and has changed very little over time.

Spontaneous generation theory

This theory by Aristotle (384–322 BC) suggests that life arose spontaneously, assuming that certain 'particles' of matter contained an 'active principle' which could produce a living organism when conditions were suitable. He was correct in assuming that the active principle was in a fertilised egg, but incorrect to extrapolate this to the belief that sunlight, mud and decaying meat also had the active principle. Louis Pasteur (1861) later demonstrated the theory of biogenesis and finally disproved the theory of spontaneous generation.

Special creation

This theory is upheld by most of the world's major religions and civilisations and attributes the origin of life to a god or supernatural event at a particular time in the past. Since the process of special creation occurred only once and therefore cannot be observed, this is sufficient to put the concept outside the framework of scientific investigation. Science concerns itself only with observable phenomena and as such will never be able to prove or disprove special creation.

Cosmozoan/panspermia theory

This theory suggests that life could have arisen once or several times, at various times and in various parts of the universe. Russian and American space probes have provided evidence that the likelihood of finding life within our solar system is remote but cannot look outside the solar system. Materials found in meteorites and comets have revealed the presence of organic molecules which may have acted as 'seeds' falling onto early Earth. There is as yet no compelling evidence to support or contradict it, particularly due to the challenges of survival and transport in space.

Biochemical evolution theory

This theory suggests that certain conditions of early Earth (see Section 1.1) generated the organic compounds and the right environment for the first production of a living organism.

Evidence leading to the support of the biochemical evolution theory

Oparin (1923)

Aleksandr Oparin suggested that organic compounds could have formed in the early Earth oceans from more simple compounds, the energy for these reactions probably being supplied from the sun's strong ultraviolet radiation before the formation of the ozone layer which now blocks out most of it. Oparin argued that, considering the amount of simple molecules in the oceans, the energy available and the time scale, it was conceivable that the oceans would gradually accumulate organic molecules to produce the 'primeval soup' in which life could have arisen. J. B. S. Haldane independently arrived at the same idea as Oparin in 1929. Oparin's hypothesis was not tested until the 1950s by Urey and Miller.

Oparin's theory has been widely accepted; however, major problems remain in explaining the transition from complex organic molecules to living organisms. This is where the theory of a process of biochemical evolution offers a broad scheme which is acceptable; however, there is no agreement as to the precise mechanism by which it may have occurred.

Oparin considered that protein molecules were crucial to the transformation to living things and through a possible sequence of events it would have produced a primitive self-replicating organism feeding on the organic-rich primeval soup. While this is supported by some scientists, others such as Sir Fred Hoyle argue that the probability of random molecular interactions giving rise to life is 'as ridiculous and improbable as the proposition that a tornado blowing through a junk yard may assemble a Boeing 747'.

Urey and Miller (1953)

In a series of experiments, Stanley Miller (a student of Harold Urey) simulated the proposed conditions of early Earth. He successfully made many substances including amino acids and simple sugars. More recently, Leslie Orgel succeeded in making a simple nucleic acid molecule in a similar experiment. Recent experiments using Miller's equipment but using mixtures of carbon dioxide and water and only traces of other gases have produced similar results to those of Miller.

Urey and Miller's experiments

SECONDARY SOURCE INVESTIGATION

BIOLOGY SKILLS

P13
P14

■ ***gather information from secondary sources to describe the experiments of Urey and Miller and use the available evidence to analyse the:***
—reason for their experiments
—result of their experiments
—importance of their experiments in illustrating the nature and practice of science
—contribution to hypotheses about the origin of life

Aim

- To describe the experiments of Urey and Miller.
- To analyse the result, reason for, importance and contribution of Urey and Miller's experiments.

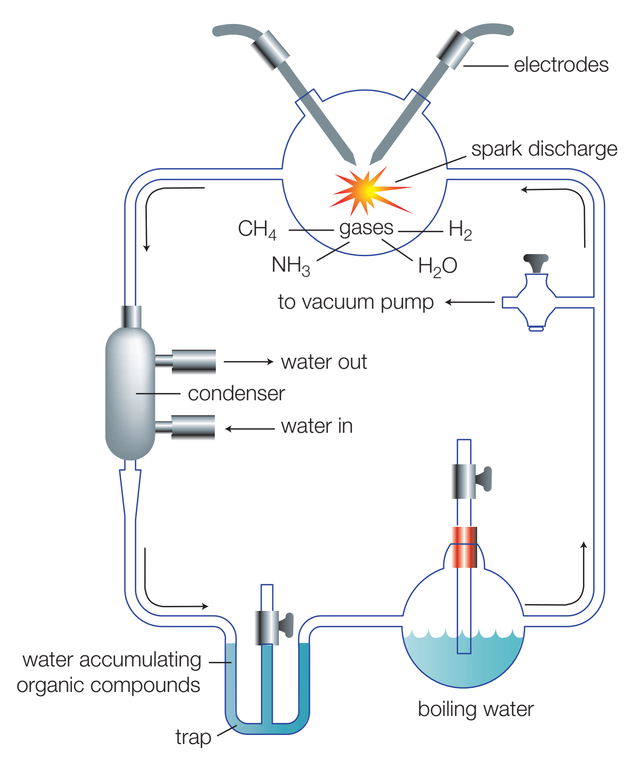
Background information

In the early 1950s, Harold Urey and his student Stanley Miller carried out the first experiment simulating hypothetical conditions present on early Earth in order to look at the chemical reactions that may have occurred. Using the equipment set up in Figure 1.1, Urey and Miller placed water, methane, ammonia and hydrogen into sealed glass tubes and flasks connected by a loop. One flask was half-filled with liquid water and the other contained a pair of electrodes. The water was heated to cause its evaporation into steam. Sparks were created between the electrodes in the other flask to simulate lightning storms in a steamy atmosphere. The steam then cooled and condensed back into liquid trickling back into the first flask, simulating an atmosphere that was cooled. This was continuously repeated simulating a cycle in the early atmosphere.

After a week, they observed that as much as 10 to 15 per cent of the carbon was now in the form of simple organic compounds, with two per cent forming amino acids. Of the amino acids formed, 13 of the 22 were those used to make proteins in living cells.

This experiment tested Oparin and Haldane's hypothesis that conditions on early Earth were favourable to chemical reactions producing organic compounds from inorganic precursors. Urey and Miller demonstrated through these experiments that organic compounds such as amino acids, which are essential to cellular life, could be made from inorganic substances under conditions hypothesised as being present on early Earth.

Figure 1.1 Miller's spark discharge reaction apparatus



Method

Read the background information provided and gather information from a variety of secondary sources on the experiments of Urey and Miller. Select the relevant information that is needed to address each aim and complete the two parts below.

Description of Urey and Miller's experiments

1. Write a one-page description (including a simplified diagram of the equipment used) of Urey and Miller's experiments.

Analysis of Urey and Miller's experiments

2. Write a paragraph for each of the following:
   (a) the reason for their experiments
   (b) the result of their experiments
   (c) the importance of their experiments in illustrating the nature and practice of science
   (d) the contribution of Urey and Miller's experiments to hypotheses about the origin of life.

Results

Once you have answered and addressed the two parts above, now summarise that information. You may choose to do this in table form and use Table 1.2 below to assist in structuring your answer, or you may prefer another method such as using point-form under subheadings.

Discussion/conclusion

1. Why were the experiments of Urey and Miller important?
2. How did they contribute to the idea of the origin of life?
3. What other scientists and their research were affected by Urey and Miller's experiments?

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Answers to Table 1.2

Table 1.2 The experiments of Urey and Miller

Description	Reason	Result	Importance in illustrating nature and the practice of science	Contribution to hypotheses about the origin of life

1.4 Urey and Miller's experiments

- ***discuss the significance of the Urey and Miller experiments in the debate on the composition of the primitive atmosphere***

Support for Urey and Miller's experiments

Urey and Miller's experiments provided the first experimental evidence that it is possible for inorganic substances to produce living (organic) substances. This has been called the theory of biochemical evolution (or the chemosynthetic origin of life). The experiments have been replicated successfully to provide a similar outcome each time. Although some scientists have argued that electrical energy might not have efficiently produced organic molecules in the atmosphere of primitive or early Earth, other energy sources such as cosmic radiation, high temperature impact events and even the action of waves on a beach could have been quite effective. Some scientists replicated experiments that have been modified using ultraviolet light instead of electricity to produce nitrogen bases and nucleotides (genetic material) as well as amino acids. In 1961, Juan Oro found that amino acids could be produced from ammonia and hydrogen cyanide solution. His experiments produced a significant amount of the nucleotide base, adenine, which is an organic compound found in **DNA** (deoxyribose nucleic acid). It is also a component of ATP (adenosine triphosphate). The results of the experiments indicate that the building blocks of life could have originated on the primitive Earth, changing from inorganic molecules to organic molecules. Scientists concluded in the 1950s that this was the significant first step in the evolution of life on Earth, and they were optimistic that the origin of life would be solved in a few decades. However, these discoveries have created a stir in the scientific community as the origin of life has not been solved.

Recent debate

There has been recent doubt concerning Urey and Miller's experiments as it is now believed that the atmosphere of early Earth did not contain free hydrogen and was not a '**reducing**' **atmosphere**. There is geological evidence for the existence of an '**oxidising'** (not free hydrogen) **atmosphere** in the precipitation of limestone (calcium carbonate) in great quantities, the oxidation of ferrous iron in early rocks and the distribution of minerals in early sedimentary rocks. There is also evidence to suggest the existence of an oxidising, (not free hydrogen) atmosphere in the composition of volcanic gases and the destruction of molecules by UV radiation. To the contrary, however, there is strong evidence to support an oxygen-free primitive Earth atmosphere in fluvial uranium sand deposits (1999) and banded iron formations documented in 1998 and 2000. In 1994, Holland documented the paleosols (ancient soils) as a source to determine atmospheric composition suggesting very low oxygen levels 2.1 billion years ago. There is also 2001 data from mantle chemistry suggesting oxygen was essentially absent from the earliest atmosphere. In 2005, simulations conducted by the University of Colorado indicated that the early atmosphere of Earth could have contained up to 40 per cent hydrogen, implying a more favourable environment for the production of organic molecules, and supporting Urey and Miller's experiments.

Another objection is that these experiments required a significant amount of energy. It is argued that although lightning storms were common on primitive Earth, they did not occur continuously as portrayed in Urey and Miller's experiment. This means that amino acids and organic compounds may have only formed in smaller amounts.

Other sources for organic compounds

Many of the organic compounds made in the Urey and Miller experiments are now known to exist in outer space. There are other sources of organic 'building blocks of life', such as meteorites, comets, and **hydrothermal vents**. The Murchison meteorite found in Victoria in 1969 was found to contain over 90 amino acids, of which 19 are found on Earth. The primitive Earth is believed to be similar to many of the comets and asteroids found in our galaxy. In 1997, Douglas C. B. Whittet published an article in *The Astrophysical Journal* on the conditions favourable to the formation of organic compounds that exist in interstellar dust clouds. If amino acids are able to survive the extreme conditions of outer space then this might suggest that amino acids were present when the Earth was first formed. More importantly, the Murchison meteorite has demonstrated that the Earth may have received organic compounds and amino acids from outside the planet.

In 2000, some scientists argued that organic compounds could have formed in areas other than the atmosphere, such as hydrothermal vents and **volcanic aquifers**.

Even though we continue to obtain more evidence towards the composition of the atmosphere of primitive Earth, each piece of evidence may support different ideas and theories. Scientists may interpret the evidence in different ways and continue to oppose each other's theories and models. Hence, the controversy and debate continues.

The experiments of Urey and Miller remain significant in the advancement of ideas surrounding the composition of the primitive atmosphere. They supported Oparin and Haldane's proposed theory and led to further experimental testing of variations in conditions favourable for the production of organic compounds.

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Extension activity—class debate

1.5 Technology has increased our understanding of the origin and evolution of life

- ***identify changes in technology that have assisted in the development of an increased understanding of the origin of life and evolution of living things***

Improved technology over the years has increased our understanding of the origin and evolution of living things. In particular, biochemical and molecular technologies have significantly improved in recent times, therefore having a profound impact on our understanding of the evolution of life.

Early technologies

(See 'Patterns in Nature' for revision.)

Early technologies included:

- glass jars and cotton—used by Francesco Redi for a spontaneous generation experiment with flies and meat, testing the idea that organisms originate directly from non-living matter
- swan-necked flasks designed and used by Louis Pasteur in his experiment for disproving the spontaneous generation theory
- the light microscope (Leeuwenhoek, 1676)—allowed us to see organisms that cannot be seen with the naked eye.

Recent technologies

Recent technologies have included:

- electron microscope development—this led to the understanding of structures at the molecular level, the remains of micro-organisms and the mineral nature of early rocks
- radiometric dating (the principle of superposition, stratigraphic correlation)—developed for dating the relative ages of fossils and surrounding rock material
- seismology—provided knowledge of the structure of the Earth and the characteristics of earthquakes
- geology—determined the composition of meteorites and volcanoes, the fossil record and geological history of the Earth
- geophysics—used the concept of continental drift and sea floor spreading (magnetic surveys) to indicate properties of the Earth's structure and age
- atomic absorption spectrophotometry —used to measure the concentration of metal elements in a rock materials

- relative proportions of stable isotopes—used to determine the absolute age of fossils
- X-ray crystallography—used to determine the structures of an immense variety of molecules and compounds
- gas and liquid chromatography (chemical separation technique)—used to isolate molecules for further study
- radioactive tracing—used to measure the speed of chemical processes
- developments in engineering have enabled both space and deep sea exploration
- amino acid and nucleotide sequencing—comparisons with ancient organic material and biological compounds today
- biochemical analysis (DNA)—comparative studies of different organisms
- genetic engineering—used to increase the understanding of relatedness between organisms and possible evolutionary pathways.

REVISION QUESTIONS

1. List the atmospheric gases believed to have existed on early Earth.
2. Describe the hypothesised environment and conditions on early Earth.
3. Identify the composition of Earth's present-day atmosphere.
4. Describe the contribution of the Murchison meteorite finding to the understanding of the origin of life.
5. Discuss the implications, to the existence of organic molecules in the cosmos, for the origin of life on Earth.
6. Describe two scientific theories relating to the evolution of the chemicals of life and their significance in understanding the origin of life.
7. Describe Urey and Miller's experiments (reason, method and result), including a simple diagram of the apparatus used.
8. Discuss the significance of Urey and Miller's experiments in the debate on the composition of the primitive atmosphere.
9. Identify three examples of different types of technology that have assisted in increasing the understanding of the origin of life and the evolution of living things.

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Answers to revision questions