



11. Origin and evolution of life (part I)

Geologists learn about the evolution of life by studying rock layers containing fossils and other traces of biological activity. The task is difficult because the geological record is incomplete. Incompleteness comes from unconformities in the stratigraphic record (see chapter 10) and processes destroying fossils (metamorphism, see chapter 8). An analogy can be made between the reconstruction of life history based on fossils and reading a book with missing pages. The study of past life based on fossils is called **paleontology**. Paleontologists assign fossils to taxonomic groups (groups defined on the basis of shared morphological characteristics), determine how and where fossil organisms lived (**paleoecology**), and study how they are related to each other from an evolutionary viewpoint.

A look at the fossil record clearly shows that the biological landscape of our planet has gone through considerable changes over time (think about the giant dragonflies of the Carboniferous or the dinosaurs of the Jurassic!). The fossil record is punctuated by extinction events and the emergence of new species. Life is not static but evolves through time.

A breakthrough in our understanding of life history came in the 19th century when Charles Darwin explained **evolution** in light of his theory of **natural selection** (a theory proposed independently by the British naturalist Alfred Russel Wallace at roughly the same time). Evolution is the process by which organisms descend from other preexisting forms of life through modifications. Individual organisms of the same species show variations in morphologic, physiologic and behavioral traits. If these traits are beneficial to the organism and increase the probability of its survival and reproduction, they will have a greater chance to be passed on from one generation to the next (hence the term “natural selection”). **Selective pressure** is any phenomenon that can reduce the ability of an individual to produce viable offspring and is the driving force of evolution in Darwin’s theory. Selective pressure can arise, for example, from climate changes or from the introduction of a new predator or the emergence of a new disease. Over many generations, the process of natural selection can influence the genetic make-up of a population and lead to the emergence of a new species (**speciation**). Advantageous traits that are inherited are called **adaptations**. Evolution by natural selection is a slow process. During rapid environmental changes, populations may not have time to adapt and entire species may face extinction. The biosphere has been affected several times by **mass extinctions** which have wiped out a large proportion of species living on the planet. However, these major disturbances were followed each time by a phase of rapid diversification as we will see in chapter 12.

In light of Darwin’s theory, life can be represented by a tree, an **evolutionary tree**, in which each branch represents a taxonomic group of organisms (Fig. 1). The branches at the very top of the tree represent extant groups. Moving down these branches means traveling back in time. The junction between two or more branches represents the time when new groups have evolved from a common ancestor. If we follow the branch of this common ancestor, we see that it too shares a common ancestor with another group. In this tree, we can find a common ancestor even for extant



groups that are very different from each other, such as eagles and slugs, if we travel back in time far enough. Darwin himself surmised that there must exist at the base of the tree one “primordial life form” from which all the others have descended (Fig. 1).

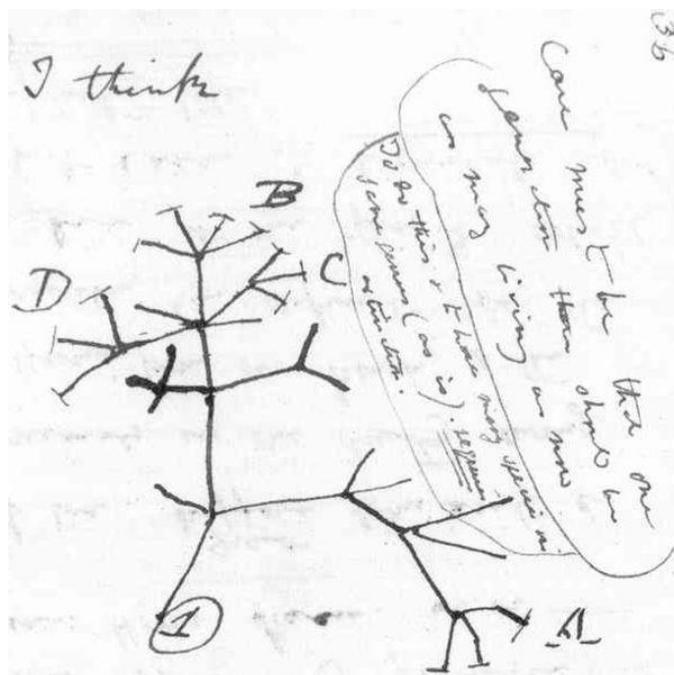


Figure 1: One of the very first illustrations of an evolutionary tree drawn by Darwin himself showing how life diversity sprang from one single common ancestor (labeled ①).

An evolutionary tree can be reconstructed on the basis of the morphologic and physiologic traits shared by organisms*. For example, we, humans, have a lot more characteristics in common with chimpanzees than with sea urchins. Therefore, our branch must be closer to that of chimpanzees and the branch of our most recent common ancestor must be relatively close to the tree top. On the other hand, the branch of sea urchins is far more distant from us and the most recent ancestor we share with them must be found further back in time, thus farther from the tree top. Comparing the morphological characteristics of extant groups of organisms does not tell us how their ancestors looked like, nor when they branched off to form new groups, and it says nothing about their relationships with extinct species. To answer these questions, scientists turn to the fossil record. For example, paleontologists have shown that the earliest birds probably emerged in the Late Jurassic and descended from dinosaurs.

Recently, molecular studies have provided new insight in the evolutionary relationships between extant groups of organisms (a discipline called **phylogenetics**). The more similar two groups are from the viewpoint of their DNA or proteins, the closer they are in the evolutionary tree and the more recent their common ancestor is. Phylogenetic studies can even provide information on the

* Dividing life in groups on the basis of shared characteristics is the job of taxonomists. The father of taxonomy is Carl Linnaeus (1707-1778) who laid down the foundation of the current system of naming and classifying organisms. The modern classification comprises the following subdivisions: domain, kingdom, phylum, class, order, family, genus, and species.



timing of divergence between two groups of organisms*. In conclusion, data from fossils and molecular studies are complementary and used together to unravel the evolutionary history of life.

11.1. The origin of life

11.1.1. What is life?

In order to answer the question of the origin of life, we must first define what life is. What distinguishes a living thing from a non-living thing? Let's consider the most basic unit of life: the cell. The simplest organisms are composed of a single cell devoid of nucleus: the **prokaryotic cell**. Prokaryotes comprise two domains of life: **bacteria** and **archaea**. They share with all other forms of life a capacity of **growth**, **reproduction**, and **evolution**. They must take up matter from their environment to grow (carbon and other elements, i.e., **nutrients**) and need a source of **energy**. The capacity of evolution is related to the transmission of **genes** from one generation to another. In all organisms, **DNA** is the molecule carrying the genetic information. DNA must be able to make copies of itself in order to pass on the genetic information to the next generation (**DNA replication**). A living cell is also characterized by a permeable **membrane** which isolates and protects the genetic material and which helps maintain an internal equilibrium (i.e. **homeostasis****). Another characteristic of life is the chemical disequilibrium it produces in the environment. For example, atmospheric O₂ would be consumed by oxidation reactions in the absence of biological activity (O₂ replenished by photosynthesis). Stable isotope fractionation is another example of life's chemical signature (see pages 6-7).

There are many ways to define life. For instance, the physicist Stephen Hawking proposes the following definition: "One can define life to be an ordered system that can sustain itself against the tendency to disorder, and can reproduce itself". From this perspective, even a computer virus could be considered as alive.

Whatever the definition of life we choose, how can we study the origin of life? The geological record can tell us a lot about primitive life forms but it cannot teach us exactly how life came to be in the first place. To investigate the origin of life, we have to turn to lab experiments.

11.1. 2. The lab approach

There are three basic ingredients needed for the emergence of life as we know it: (1) **water**, (2) **organic molecules**, and (3) **energy**. Water is an essential constituent of life. The body weight of some organisms is composed of 90% of water! Water is also an excellent solvent and can transport compounds involved in chemical reactions. Organic molecules are composed of a backbone of carbon atoms linked to other elements, primarily H, O, N, P and S***. Energy is

* The technique is referred to as "molecular clock". The rate of modifications in DNA and proteins is roughly constant among groups of organisms. Therefore the differences between the DNA and proteins among distinct groups of organisms can be used to infer the amount of time elapsed since they diverged from a common ancestor.

** Definition of the Cambridge Dictionary: "The ability or tendency of a living organism, cell, or group to keep the conditions inside it the same despite any changes in the conditions around it, or this state of internal balance".

*** C, H, O, N, P, S: the 6 elements essential for life are also among the most common elements in the universe!



needed to build the large organic molecules needed to sustain life (e.g. proteins, RNA, DNA). Here are three important steps toward the formation of a living cell:

① *Formation of simple organic molecules*

The first breakthrough in our understanding of the origin of life came in 1953 with the **Miller-Urey experiment** (Fig. 2). Its aim was to reproduce the conditions existing on the early Earth and find out whether organic molecules could be produced in such conditions. The experiment used water vapor and a mixture of gases (CH_4 , NH_3 , H_2 , and H_2O) to simulate the primitive atmosphere* and an electric arc as a source of energy to mimic the effect of lightning. Under these conditions, numerous organic molecules could be synthesized, including a variety of amino acids (basic structural units of proteins). Other experiments using the same approach but with different mixtures of chemical compounds succeeded in synthesizing nucleotides, key components of RNA and DNA.

Another hypothesis suggests that organic compounds may have been carried to Earth by meteorites and comets. A chemical analysis of the Murchison meteorite showed that it contains various organic molecules, including amino acids!

In conclusion, large amounts of organic molecules must have existed on the early Earth. However, the absence of an ozone layer** implies that they were exposed to intense UV radiations. Life must have formed in an environment protected from these radiations, such as the underside of rocks or at some depth under water.

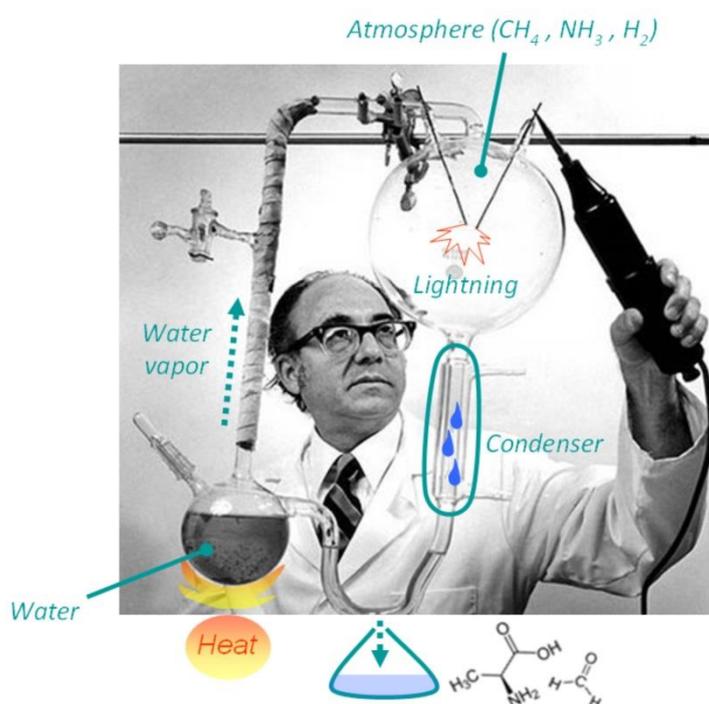


Figure 2: The Miller-Urey experiment

* Note that there was no free oxygen in the primitive atmosphere. Oxygen was produced later by photosynthesis.

** Ozone (O_3) is produced in the upper atmosphere by the reaction $\text{O}_2 + \text{O} \rightarrow \text{O}_3$ in which O comes from the dissociation of O_2 by solar radiation



② Formation of complex organic molecules capable of self-replication (RNA, DNA)

The next step toward the emergence of life is the formation of complex organic molecules (polymers like RNA consisting of a chain of nucleotides). RNA is similar to DNA but instead of being double-stranded and helical, it is formed of a single strand of nucleotides. Biochemists have shown that clay minerals can promote the assembly of nucleotides into strands of RNA. DNA is like a blueprint that carries the information needed for building proteins. However, DNA does not directly communicate with the protein factory. Instead, RNA is used to copy the information stored in DNA (**transcription**) and carry it to the protein factory (Fig. 3A). It is also involved in other tasks like delivering the building units of proteins (i.e., amino acids). During cell division, DNA replicates itself so that the genetic information is passed on to the daughter cells (Fig. 3B). **DNA replication** requires protein enzymes to split the double-stranded DNA molecule and help connecting each strand with free nucleotides. The information for building these proteins is encoded in DNA. Life as we know it is therefore based on complex interactions between DNA, RNA and proteins. How to bridge the gap between the “prebiotic soup” and a complex DNA-based (living) system? One possible scenario involves RNA. RNA is a versatile molecule that can encode genetic information and be the catalyst of its own replication. RNA could potentially have sustained a simple form of life before evolving into the more complex DNA-based system. This hypothesis is referred to as the **RNA-world hypothesis**.

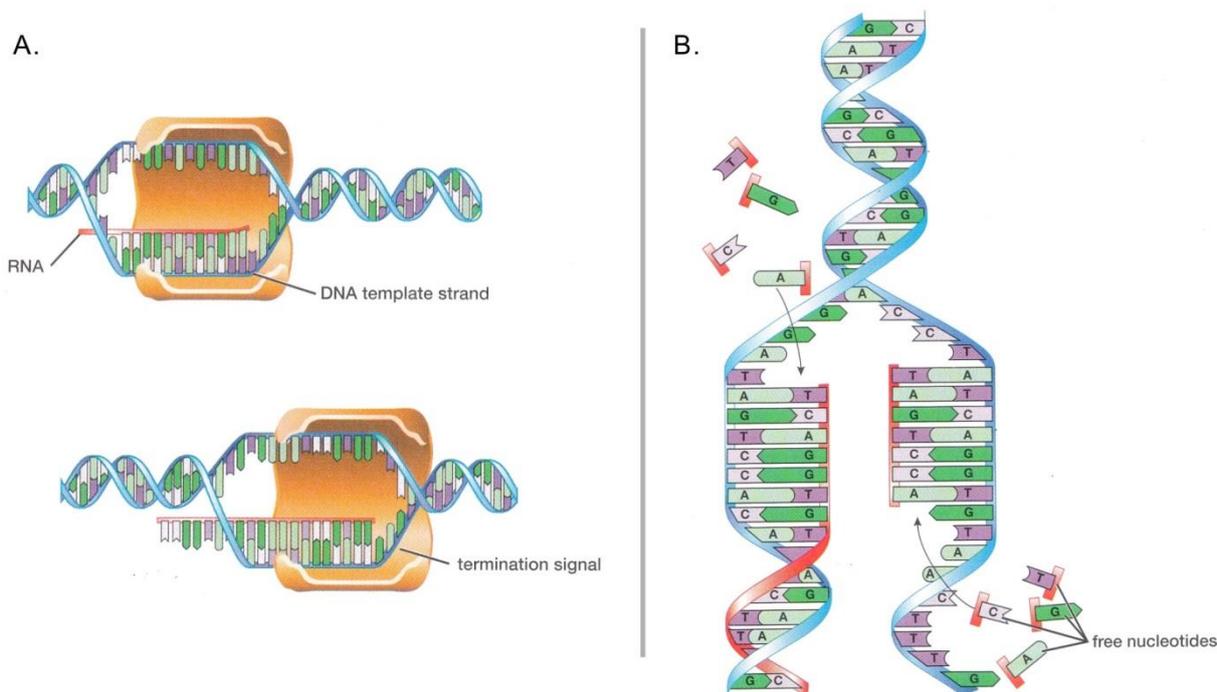


Figure 3: A. RNA transcription, B. DNA replication (source: Biology, Life on Earth, 9th ed.).

③ Formation of membrane-bound vesicles capable of self-reproduction

It has been shown that lipid vesicles can form abiotically and even divide spontaneously under



certain conditions (Fig. 4). The first protocell may have been composed of such lipid vesicles enclosing an information-carrying molecule such as RNA. Spontaneous division of these vesicles must have occurred in parallel with the self-replication of information-carrying molecules, leading to the transfer of the genetic code from one generation of protocells to the next. Many of these protocells must have failed but those which bore advantageous modifications carried on their division and evolved by natural selection toward life as we know it.

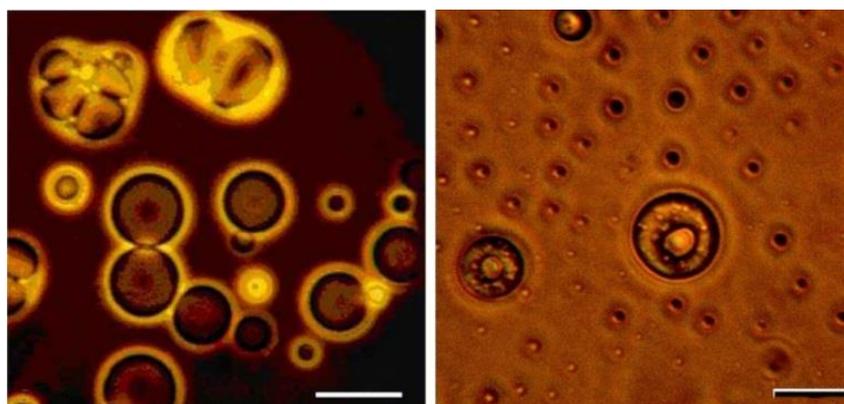


Figure 4: Lipid vesicles produced in the lab (sources: Deamer et al., 2002; Dworkin et al., 2001).

11.2.2. Evidence from the geological record

The geological record can provide information on the environmental conditions existing on the early Earth. In addition, from the oldest Precambrian fossils we can learn about the first primitive forms of life and the early phase of biological evolution.

The Earth is 4.56 Ga* old. Life would have had a hard time to form before 3.9 Ga because of repeated and violent meteorite impacts and a surface temperature above 100°C (remember the so-called “Heavy Bombardment” mentioned in chapter 2). However, evidence from the rock record in Canada suggests that the Earth’s landscape was already characterized by ocean basins and continents shaped by plate tectonics more than 3.95 billion years ago**. Early evidence for the deposition of sediments under water was also reported from a 3.8 Ga rock formation in Greenland. Moreover, there was no or very little O₂ in the atmosphere and the first cellular life forms must have been anaerobic prokaryotes. Volcanic eruptions released gases such as CO₂, H₂S, SO₂, and N₂. Other gases that may have been present in the atmosphere are CH₄, NH₃, and H₂. The relative proportion of these gases is still debated.

Evidence for biological activity in the geological record can be classified in 4 categories:

* Ga stands for Giga Annum which means 1 billion years in Latin.

** Recent geochemical analyses of sedimentary rocks from the same area suggest biological activity was already going on more than 3.95 billion years ago (Tashiro et al. 2017, *Early trace of life from 3.95 Ga sedimentary rocks in Labrador, Canada*, Nature 549, 516-518)



① *Morphologic evidence*

Microfossils and microbial mats can be preserved in sedimentary rocks which have been relatively unaffected by metamorphism.

② *Biomineralization*

There are two types of biomineralization: direct and indirect. An example of direct biomineralization is the precipitation of CaCO_3 by organisms to build a shell or skeleton (e.g., bivalves, reef corals). Minerals can also be a byproduct of biological activity (indirect biomineralization). An example of indirect biomineralization is the precipitation of CaCO_3 in relation with bacterial growth in stromatolites (see section 7.6.2.). In conclusion, the presence of specific minerals in rocks can indicate a possible link with biological activity.

③ *Stable isotope fractionation*

Stable isotope fractionation is the process by which stable isotopes are segregated on the basis of their mass during physicochemical or biochemical processes. For example, the evaporation of water involves the fractionation of the stable isotopes of oxygen. The ratio $^{18}\text{O}/^{16}\text{O}$ of the water molecules in water vapor tends to be lower than in the liquid from which it evaporated. That is because the water molecules escaping from the liquid and turning into a gas tend to be enriched in ^{16}O (the “light” isotope of oxygen). Similarly, biological processes produce isotope fractionation. Photosynthesis, for example, produces organic compounds enriched in ^{12}C relative to ^{13}C . Therefore, the isotopic analysis of sedimentary rocks can yield important clues regarding the occurrence and nature of biological processes.

④ *Biomarkers*

Biomarkers are large organic molecules produced by living organisms (e.g. polypeptids, triterpenes, and steranes). Their presence in sedimentary rocks provides a strong evidence for biological activity. Moreover, biomarkers may also give an indication on the type of organisms from which they derived. For example, the organic compound called algaenan is exclusively produced by green algae.

Evidence provided by stable isotopes suggests that biological activity existed as early as 3.8 Ga, and perhaps even earlier (see reference in footnote on previous page). The first morphologic evidence comes from the remains of microbial mats (stromatolites) and microfossils discovered in Australia in a 3.5 Ga old rock formation (although this claim has been challenged). There are multiple lines of evidence suggesting a diverse microbial life between 3.4-3.2 Ga.

In conclusion, we can infer from the geological record that life may have formed as early as 3.8 Ga (or even earlier based on geochemical signature of sedimentary rocks) and was very likely present (and consisted of diverse microbial life forms) by 3.4 Ga.