Life’s Origin and History

The age of the earth is estimated at about 4.5 billion years based on: the age of meteorites, moon rocks, and the oldest rocks on earth (3.9 billion years old). The earliest sedimentary rocks are about 3.8 billion years old and these contain organic deposits.

![Diagram showing the timeline of life's origin and history.](image)
The first definite microfossils date from 3.5 to 3.6 billion years resemble modern stromatolites - mats of blue-green algae. It is clear that life got started very early in Earth’s history.
How did life begin?

Life - a highly organized chemical system that is able to maintain itself and reproduce.

One hypothesis is that life came here from elsewhere - another planet either in our solar system or outside our solar system. This is the "Panspermia Hypothesis."

• life came here unaided as a spore from another solar system (several thousand solar systems are within 100 light years)
• life came here from another solar system aided by an intelligent life form (e.g. Voyager)
• life came here from another planet in our solar system (e.g. Mars rocks)

This hypothesis begs the question of how life got started elsewhere and, at this point, can’t be investigated scientifically
Working hypothesis: Life originated from chemical building blocks on earth.

If life organized itself according to physical laws it can be investigated scientifically.

If it can be shown that one of the properties of life, or one of the basic building blocks of living systems, could not have become organized on its own under conditions that existed in the past, then we would have to reject the working hypothesis.

It is clear that it would be difficult for amino acids, proteins, and nucleic acids to become organized today because of the high concentration of oxygen in the atmosphere and surface waters. Any high-energy compound will donate its electrons to any ready electron acceptor. Oxygen is a good electron acceptor.

So, the environment of early earth must have been different than today. It must have not have had many oxidizing agents. The environment must have been a reducing environment.
Is there evidence that early earth had a reducing environment?

Other planets in our solar system (Venus, Mars, Jupiter, Saturn, and Uranus) all have reducing atmospheres - rich in CH₄, CO₂, CO, H₂S, NH₃

Sediments that were laid down prior to 2.5 bya contain reduced chemical compounds. After 2.2 bya the chemicals deposited in sediments tend to be oxidized.

Reduced Iron (Ferrous Iron - Fe⁺⁺) is soluble in water
Oxidized Iron (Ferric Iron - Fe⁺⁺⁺) is insoluble in water
The “red-beds” or “banded iron formations” were created as soluble iron was oxidized and precipitated out of solution in the earth’s oceans.

It appears that oxygen was rare in the earth’s atmosphere until about 2.2 bya.
Can complex chemicals form in a reducing atmosphere?

1953 - Miller and Urey created an apparatus to address the question.

Used atmosphere of CH\textsubscript{4}, NH\textsubscript{3}, H\textsubscript{2}, and H\textsubscript{2}O and used electrical discharges as a source of energy (simulated lightning).

After a few days the mixture yielded some amino acids, HCN, H\textsubscript{2}CO (formaldehyde), and these subsequently reacted to produce sugars, purines, and pyrimidines.

Later experiments showed that heat or UV radiation and other mixtures of gases lacking oxygen produced similar results.
Current estimates of the amounts of methane and ammonia that were present in Earth’s early atmosphere suggest that over time oceans would have been rich in organic molecules with a concentration similar to weak chicken broth. That broth has been labeled the “prebiotic soup” or “primordial soup.”
Macromolecules are necessary for life. **Could polymers (proteins, nucleic acids) of the building blocks have formed?**

This is a potential problem because polymers form through dehydration syntheses. In aqueous environments hydrolysis is more likely.

Fox found that dry mixtures of amino acids spontaneously polymerize at 130°C. Amino acid adenylates (amino acids charged with ATP) form random polymers spontaneously at 60°C. Huber found if CO was added to the mixture there was a preference for stable peptide bonds between amino acids.

The primordial soup may have been dried on hot rocks or in evaporating pools to become a “primordial pizza” where spontaneous polymerization would have been favorable.
CTP, GTP, TTP, UTP when placed together at 55°C spontaneously form polymers.

However, the polymers are 5’→3’ and 5’→2’ in orientation. The addition of zinc results in only 5’→3’ polymerization. (Today DNA polymerase and RNA polymerase require zinc as a cofactor.)

DNA and RNA are autocatalytic with or without polymerases when placed in mixtures of triphosphate nucleotides. Some RNA molecules are catalytic (ribozymes) and can promote the formation of complimentary copies of themselves.

So if nucleic acids were present they would spontaneously create complimentary copies of themselves.
Spiegelman and colleagues showed that a test tube RNA replication systems evolves in response to different selective regimes.
A theoretical model for a self-replicating system

The R3C ribozyme can catalyze the formation of copies of itself.
Life requires isolation from the surrounding environment for the maintenance of order. **Can compartmentalized systems form spontaneously?**

Phospholipids spontaneously form lipid bilayers and micelles.

Lipid bilayers exhibit many properties of cell membranes - selective permeability and accumulation of some chemicals.

Mixtures of polymers also form coacervates - polymer rich droplets that can be stable in solution.
Various models suggest how chemical systems could have initially become isolated from the surrounding medium.

Droplet systems have been created that can grow and split into new droplets.
Mutualism between replicating systems has been suggested as a mechanism for the evolution of the first cells. If one of the systems also causes the formation of membranes surrounding the mutualists then natural selection can act on their combined abilities to create more copies of themselves.
The field of prebiotic chemistry is still young and there are many unanswered questions and unresolved problems.

For example - Lipids can be synthesized in nonliving systems but the fatty acids tend to be branched. Such lipids will not form lipid bilayers or micelles.

The major unanswered question is how protein based enzyme systems evolved. The best supported hypothesis is that they evolved from short polypeptides that originally served as coenzymes for ribozymes.

Initial work in prebiotic chemistry has had enough positive results to suggest that further work may resolve the problems and unanswered questions.
If life originated 3.6 bya in a reducing environment, the early life forms must have been anaerobes. **Were early cells anaerobic?**

Most of the Archaebacteria are obligate anaerobes. Many of the Eubacteria are obligate anaerobes and most of the remainder are facultative aerobes.

A comparison of nucleotide similarities in ribosomal RNA suggests that the most primitive prokaryotes are thermophilic. They live in hot anaerobic environments.

Other important anaerobes include N fixers and purple sulfur bacteria.
Oxygen generating photosynthesis was a prerequisite for aerobic metabolism. Eukaryotes are all aerobic. **Is there evidence that photosynthesis originated before eukaryotes?**

The first red-beds (sediments rich in oxidized iron) are 2.5 byo. Most of the red-beds are about 2.2 byo.

The first microfossils that are large enough to be eukaryotes are about 1.7 byo. Unquestionable eukaryotic microfossils date to 0.9 bya.

(a) Grand Canyon shales (800 million years old)  
(b) Utah shales (950 million years old)  
(c) Central Australian sediments (850 million years old)
How did eukaryotes originate?

Eukaryotic evolution involved the development of symbiotic associations among prokaryotes. The associations produced fitness advantages because of increased metabolic abilities.

This is the endosymbiotic theory for the origin of eukaryotes.

Several organelles in eukaryotes appear to be descended from prokaryotic ancestors.

Mitochondria, chloroplasts, and flagella are likely to have had a symbiotic origin.
Horizontal transfers of symbiotic organisms were important in the origin of eukaryotes. Mitochondria are descended from free-living purple bacteria and chloroplasts are descended from free-living cyanobacteria.
Mitochondria and Chloroplasts:
• The double membrane structure of both is similar to what is seen in symbiotic parasitic prokaryotes like *Rickettsia*, with the inner membrane belonging to *Rickettsia* and the outer membrane being that of the host cell.
• Both possess their own DNA that is very similar to that found in free-living prokaryotes
• Both have ribosomes that are more similar to prokaryotic ribosomes in size and structure than to cytoplasmic ribosomes
• Both have the ability to multiply independently within the cytoplasm
• Chloroplasts have the same form of chlorophyll as cyanobacteria (blue-green algae)
Similar associations have evolved repeatedly - free-living cyanobacteria gave rise to chloroplast-like structures in protists multiple times.

*Paramecium bursaria* harbors algal cells that can be cultured outside its cytoplasm.

Many photosynthetic eukaryotes have secondary and tertiary chloroplasts - eukaryotic symbionts that have chloroplasts derived from symbiotic cyanobacteria.
The geologic time scale was developed through observations of change in the composition of fossils in different strata.
Paleozoic Life - The Cambrian Explosion

The Cambrian period began 542 mya. Early in the Cambrian few multicellular animals were found but from 530 mya to 515 mya nearly all modern phyla with skeletons or hard body parts became common in the fossil record. Many groups that no longer exist also became common.
The most primitive multicellular animals are sponges. Sponges evolved from choanoflagellates - filter-feeding colonial protists.

Once multicellularity - differentiation of tissues with different functions - was perfected it appears that many different body plan options evolved. It was a period of evolutionary “experimentation” through adaptive radiation.
Molecular evidence, using the assumption of a molecular clock, suggests that multicellularity may have existed as much as 1 by before the Cambrian. Hard body parts may have originated first in the Cambrian, making fossilization more likely.

The first vertebrates, and the first organisms that produced cellular bone evolved in the Cambrian.

A mass extinction at the end of the Cambrian (500 mya) resulted in the loss of many groups that had formerly been common.
Ordovician Period (488 - 444 mya)

Animal phyla diversified again within the Ordovician - especially the echinoderms and molluscs. Starfish and nautiloids were the major predators.

An ice age and a major extinction ended the period.
Silurian (439 mya) and Devonian Periods (408 mya)

During the Silurian the first jawed vertebrates evolved: the Placoderms and Acanthodians. They also had paired appendages.

During the Devonian the two major lineages of bony fishes evolved, Sarcopterygian (lobe-finned) fishes and Actinopterygian (ray-finned) fishes evolved.
Plants were the first terrestrial eukaryotes. The first colonization occurred in the early Ordovician. Most modern plant phyla have fossil records from the Silurian and Devonian. Major plant evolutionary events were the development of vascular systems, structural support, a shift from a dominant gametophyte to a dominant sporophyte, and the development of seeds.
Animals followed the plants onto the land in the Devonian. The first land animals were arthropods - from the two major lineages that exist today - the chelicerates (spiders, scorpions, mites) and mandibulates (millipedes, centipedes, insects).

Ichthyostegids were the first tetrapods. They colonized the land in the late Devonian.
Carboniferous (359 mya) and Permian (299 mya)

World-wide tropical climates supported lush forests of ferns and horsetails - that gave rise to many coal deposits. Seed plants, with wind pollination began to diversify. Winged insects originated, and the first with complete metamorphosis also evolved.

Amphibians were diverse and gave rise to the first amniotes - the captorhinomorphs. Early amniotes included the synapsids (which eventually gave rise to mammals), and diapsids which gave rise to the dominant reptiles of the Mesozoic.

At the end of the Permian, over a period of 5 to 8 million years, the largest mass extinction ever occurred. As many of 96% of all marine species represented in the fossil record in the Permian did not survive. The impact on terrestrial life was much less.
A captorhinomorph – an early amniote – a stem reptile
Mesozoic Life - The Age of Reptiles

Three periods comprise the Mesozoic - Triassic (251 mya), Jurassic (200 mya), and Cretaceous (145 mya).

The few groups of marine species that survived the end of the Paleozoic diversified greatly in the Triassic - esp. molluscs, corals, bony fishes.

Many marine groups were decimated again at the end of the Triassic. The species that survived began the “Mesozoic Marine Revolution” - a coevolutionary arms race between molluscs and their predators - fishes and crabs with the ability to crush shells.

Terrestrial plants were predominantly gymnosperms. Flowering plants first appeared in the early Cretaceous. At the same time most modern insect groups, including the social forms had evolved.
At the end of the Cretaceous an asteroid impact resulted in the extinction of many terrestrial and marine groups. The change is well-recorded in the fossil record as the “K/T boundary.”
Cenozoic Life - The Age of Mammals

The Cenozoic comprises two periods, the Tertiary (65 mya) and the Quaternary (1.8 mya).

A relatively cool dry climate promoted the growth of grasslands on most continents. Glaciations began in the late tertiary and have continued through the quaternary. Today we’re in a period of global warming and glacial retreat.
Some new marine groups originated in the Cenozoic (sand dollars) and teleost fishes became the most diverse group of vertebrates. Water sequestered in glaciers lowered sea levels and resulted in extinction of many shallow water molluscs.

Flowering plants and insect pollinators coevolved and diversified greatly. Grasses became dominant in the dry and fire-prone interior of continents. Small herbs became common - many developed from woody ancestors.

Birds and snakes began world-wide adaptive radiations.
Marsupial and placental mammals originated in the Cretaceous, but most were small and left little record. Modern mammals adaptively radiated into the niches that had been occupied by reptiles in the Mesozoic.
Marsupials were once common on all continents. Today they are only found in Australia and South America (the opossum is a recent immigrant to North America).

South America was isolated from the other continents throughout much of the early Cenozoic and placental and marsupial mammals diversified there in isolation from mammalian diversification on other continents - including sloths, anteaters, and armadillos. The connection of North and South America through the Isthmus of Panama resulted in the exchange of species between the continents, but today few South American species survive.
Primates originated 33 mya, and the first apes date to 22 mya.

Rodents became the most diverse group of mammals.

Elephants and their relatives became very diverse in the middle Cenozoic, but today only two species survive. Woolly mammoths lived until about 13,000 years ago.
Ungulates comprise two lineages - the artiodactyls or even-toed ungulates (cows, pigs, antelopes, hippos) and perissodactyls or odd-toed ungulates (horses, rhinos, tapirs). Both groups diversified on the grasslands of the old-world and North America. Artiodactyls also gave rise to cetaceans and the group has been renamed as Cetartiodactyls.

Periods of dramatic global temperature change began about 3 mya. Sea levels fell and rose with glacial advances and retreats. Low sea levels allowed species to move among the continents through the Bering Land Bridge and between Asia, Indonesia, and Australia.
The Pleistocene has been marked by the extinction of many large mammal and bird species - likely due to human exploitation or competition. Some recent evidence suggests another asteroid impact may also have been involved.

Modern humans are the most significant source of ecosystem change since the K/T asteroid impact and have increased the rate of species extinction by approximately 7000 times the background rate. Humans have deforested much of the tropics and temperate zones, promoted desertification through overgrazing by domesticated animals, eliminated habitats for many species through agriculture and development, overexploited marine resources, polluted air and water, and contributed to global warming through the burning of fossil fuels. Human impacts are accelerating because human population growth is exponential. The current mass extinction event will be one of the greatest and one of the most rapid.