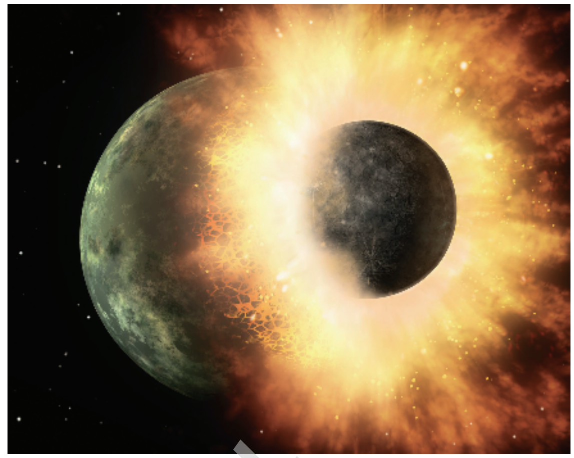
ONE

The Origin of Life on Earth



In This Chapter

First, I describe what geology and paleontology aim to study. But in dealing with the history of life, we have to face the most difficult question first: where did Earth's life come from? Astronomers find that organic compounds exist almost everywhere in space, yet we only know of life on one planet: Earth. I discuss the planets and moons of our solar system, and there are good reasons why none of them (except Earth) have life. Life exists in cells, so I discuss at length how complex organic molecules might have come together inside cells which survived, reproduced, and evolved on the early Earth. Laboratory experiments have already mimicked many of the steps in that process in the laboratory, but there is still a lot of work to be done.

How Geology Works

Geology is the study of the Earth we live on. It draws on methods and principles of its own, but also draws from many other sciences: physics, chemistry, biology, mathematics, and statistics are just a few. Geologists cannot be narrow specialists, because geology is a broad science that works best for people who think broadly. So geologists cannot be successful if they are geeks (though a few seem to manage it). Above all, geology deals with the reality of the Earth: its rocks, minerals, its rivers, lakes and oceans, its surface and its deep structure. Always, the reality of evidence from field work controls what can and what cannot be said about the Earth. Geological ideas are tested against evidence from rocks, and many beautiful ideas have failed that demanding test.

Some geologists deal with Earth as it is now: they don't need to look at the past. Deep Earth history doesn't matter much to a geologist trying to deal with ecological repair to an abandoned gold mine. But many geologists do study Earth history, and they find that our planet has changed, at all scales of space and time, and sometimes in the

History of Life, Fifth Edition. Richard Cowen.

most surprising ways. For 200 years, fossils have provided direct and solid proof of change through time. Life began and evolved on a planet that is changing too. Fossils often provide insight into Earth's environmental changes, whether or not they survived those changes. Paleontology is not just a fascinating side branch of geology, but a vital component of it.

As they run their life processes, organisms take in, alter, and release chemicals. Given enough organisms and enough time, biological processes can change the chemical and physical world. Photosynthesis, which provides the oxygen in our atmosphere, is only one of these processes. In turn, physical processes of the earth such as continental movement, volcanism, and climate change affect organisms, influencing their evolution, and, in turn, affecting the way they affect the physical earth. This gigantic interaction, or *feedback mechanism*, has been going on since life evolved on Earth. Paleontologists and geologists who ignore this interaction are likely to get the wrong answers as they try to reconstruct the past.

How Paleontology Works

Traces of Earth's ancient life have been preserved in rocks as fossils. Paleontology is the science of studying these fossils. Paleontology aims to understand fossils as once-living organisms, living, breeding, and dying in a real environment on a real but past Earth that we can no longer touch, smell, or see directly. We perceive a virtual Earth through our study of fossils and the rocks they are preserved in.

Most paleontologists don't study fossils for their intrinsic interest, although some of us do. Their greater value lies in what they tell us about ourselves and our background. We care about our future, which is a continuation of our past. One good reason for trying to understand ancient life is to manage better the biology of our planet today, so we need to use some kind of reasonable logic for clear interpretation of the life of the past.

Some basic problems of paleontology are much like those of archaeology and history: how do we know we have found the right explanation for some past event? How do we know we are not just making up a story?

Anything we suggest about the biology of ancient organisms should make sense in terms of what we know about the biology of living organisms, unless there is very good evidence to the contrary. This rule applies throughout biology, from cell biochemistry to genetics, physiology, ecology, behavior, and evolution.

But suggestions are only suggestions until they are tested against real evidence from fossils and rocks. Since fossils are found in rocks, we have access to environmental information about the habitat of the extinct organism: for example, a rock might show clear evidence that it was deposited under desert conditions, or on a shallow-water reef. Thus fossils are not isolated objects but parts of a larger puzzle. For example, it is difficult to interpret the biology of the first land animals unless we consider environmental evidence preserved in the Devonian sediments in which they are preserved (Chapter 7).

An alert reader should be able to recognize four levels of paleontological interpretation. First, there are *inevitable conclusions* for which there are no possible alternatives. For example, there's no doubt that extinct ichthyosaurs were swimming marine reptiles. At the next level, there are *likely interpretations*. There may be alternatives, but a large body of evidence supports one leading idea. For example, there is good evidence that suggests ichthyosaurs gave birth to live young rather than laying eggs. Almost all paleontologists view this as the best hypothesis, and would be surprised if contrary evidence turned up.

Then there are *speculations*. They may be right, but there is not much real evidence one way or another. Paleontologists are allowed to accept speculations as tentative ideas to work with and to test carefully, but they should not be surprised or upset to find them wrong. For example, it seems reasonable to me that ichthyosaurs were warm-blooded, but it's a speculative idea because it's difficult to test. If new evidence showed that the idea was unlikely, I might be personally disappointed but I would not be distressed scientifically.

Finally, there are *guesses*. They may be biologically more plausible than other guesses one might make, but for one reason or another they are untestable and must therefore be classified as nonscientific. For example, if I asked an artist to draw me an ichthyosaur (Fig. 1.1), I might suggest bold black-and-white color patterns, like those of living orcas, but another paleontologist might opt for more muted patterns like those of living fishes. Both ideas are reasonable, and are surely better science than one might find in a piece of art, however pleasing it may be (Fig. 1.1c). But all these are guesses: there is no evidence at all.

You will find examples of all four kinds of interpretation in this book. Often it's a matter of opinion in which category to place different suggestions, and this problem has caused many controversies in paleobiology. Were dinosaurs warm-blooded? For most paleobiologists this is an inevitable conclusion from the evidence. Some think it's likely, some think it's only speculative, some think it's unlikely, and a few think it is plain wrong. New evidence almost always helps to solve old questions but also poses new ones. Without bright ideas and constant attempts to test them against evidence, paleontology would not be so exciting.

The fossil record gradually gets poorer as we go back in time, for two reasons. Biologically, there were fewer types of organisms in the past. Geologically, relatively few rocks (and fossils) have survived from older times, and those that have survived have often suffered heating, deformation, and other changes, all of which tend to destroy fossils. Earth's early life was certainly microscopic and soft-bodied, a very unpromising combination for fossilization. So direct evidence about early life on Earth is very scanty, though speculation and guesses are abundant.

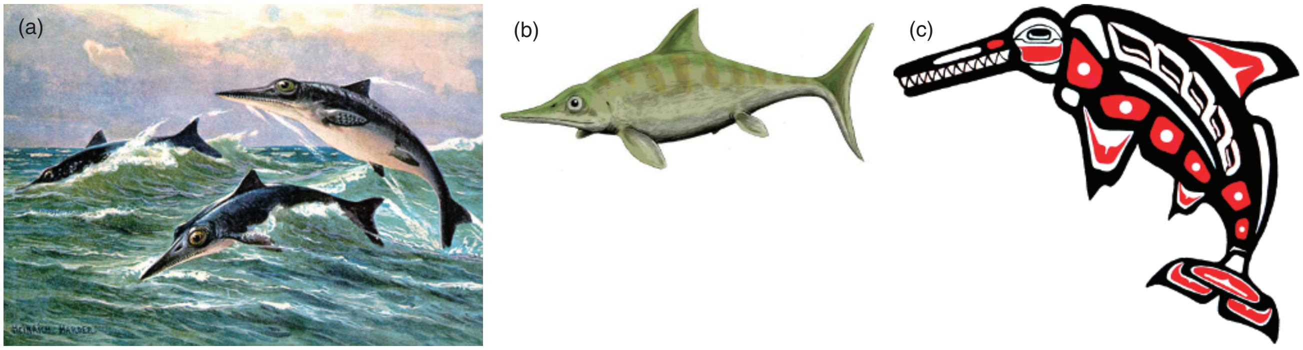


Figure 1.1 Guesses about ichthyosaur color patterns. a) ichthyosaur painting by Heinrich Harder 1916. b) art by Nobu Tamura, with muted colors, placed into Wikimedia. c) stylistic art work © Danny Anduza, used by permission. See more of Danny's work at http://www.cafepress.com/dannysdinosaurs

Figure 1.2 Edgar Rice Burroughs published the fourth in his series of Martian stories, *Thuvia, Maid of Mars*, as a book in 1920. a) cover art by P. J. Monahan; b) scene for black-and-white inside art, by J. Allen St John. The beast is a thoat, based on the real Earth fossil *Thoatherium* from South America (wait for Chapter 16!).

The Origin of Life

The fact of observation is that there is no evidence of life, let alone evidence of intelligence or civilization, anywhere in the universe except on our planet, Earth (for example, Smith 2011). This fact comes in the face of strenuous efforts by science fiction writers, tabloid magazines, movie directors, and NASA publicists to persuade us otherwise (Fig. 1.2). However, we have to face up to its implications. Most important, it implies (but does not prove) that Earth's life evolved here on Earth. How difficult would that have been?

We can test the idea that life evolved here on Earth, from nonliving chemicals, by observation and experiment. Geologists and astronomers look for evidence from the Earth, Moon, and other planets to reconstruct conditions in the early solar system. Chemists and biochemists determine how complex organic molecules could have formed in such environments. Geologists try to find out when life appeared on Earth, and biologists design experiments to test whether these facts fit with ideas of the evolution of life from nonliving chemicals.

Complex organic molecules have been found in interstellar space, in the dust clouds around newly forming stars, on comets and asteroids and interplanetary dust, and on the meteorites that hit Earth from time to time. These compounds form naturally in space, generated as gas clouds, dust particles, and cometary and meteorite surfaces are bathed in cosmic and stellar radiation. Laboratory experiments designed to mimic such conditions in space have yielded organic molecules. Probably any solid surface near any star in the universe received organic molecules at some point in its history (Ciesla and Sandford 2012). Analyses of meteorites that have hit the Earth show they were carrying many of the basic organic molecules needed in the evolution of life.

But life as we know it is not just made of organic compounds: life consists of cells, composed mostly of liquid water that is vital to life. It is almost impossible to imagine the formation of any kind of water-laden cell in outer space: that can only happen on a planet that had oceans and therefore an atmosphere.

Planets have organic compounds delivered to them from space, especially from comets or meteorites, but this process by itself is unlikely to lead to the evolution of life. For example, organic molecules must have been delivered everywhere in the solar system, including Mercury, Mars, Venus, and the Moon, only to be destroyed by inhospitable conditions on those lifeless planets.

If conditions on a planet's surface were mild enough to allow organic molecules to survive after they arrived on comets, it is very likely that organic molecules were also forming naturally on that planet too. Space-borne molecules may have added to the supply on a planetary surface, but they are unlikely to have been the only source of organic molecules there.

Planets in Our Solar System

Scientists reconstructed the process of star and planet formation long before we could check it by observing stars forming out in the universe. Stars form from collapsing clouds of dust and gas, and in the process, planets and smaller bodies often form in orbit around the new stars. Now that we have telescopes powerful enough, the theories have been confirmed. In 2010 a spectacular new star, surrounded by dust and gas, was discovered in the process of forming in the constellation Centaurus (Fig. 1.3). Astronomers have now found hundreds of planets around other stars, most of them large ones because they are easier to detect.

Our star the Sun formed with Earth as one of four terrestrial (rocky) planets in the inner part of our solar system. Venus and Earth are about the same size, and Mars and Mercury are significantly smaller. They all formed from dust and gas in the same way, about 4570 Ma (million years ago) (Lin 2008).

Most likely, all the planets were largely complete by 4500 Ma, though they were bombarded heavily for hundreds of millions of years afterwards as stray asteroids struck their surfaces. The heat energy released as the planets formed would have made them partly or totally molten. Clearly, a very young planet is not a place where life could evolve. Earth in particular was struck by a huge Mars-sized body late in its formation. That impact probably melted the entire Earth, while most of the debris collected close to Earth to form the Moon (Fig. 1.4).

All the inner planets melted deeply enough to have hot surfaces that gave off gases to form atmospheres. But there

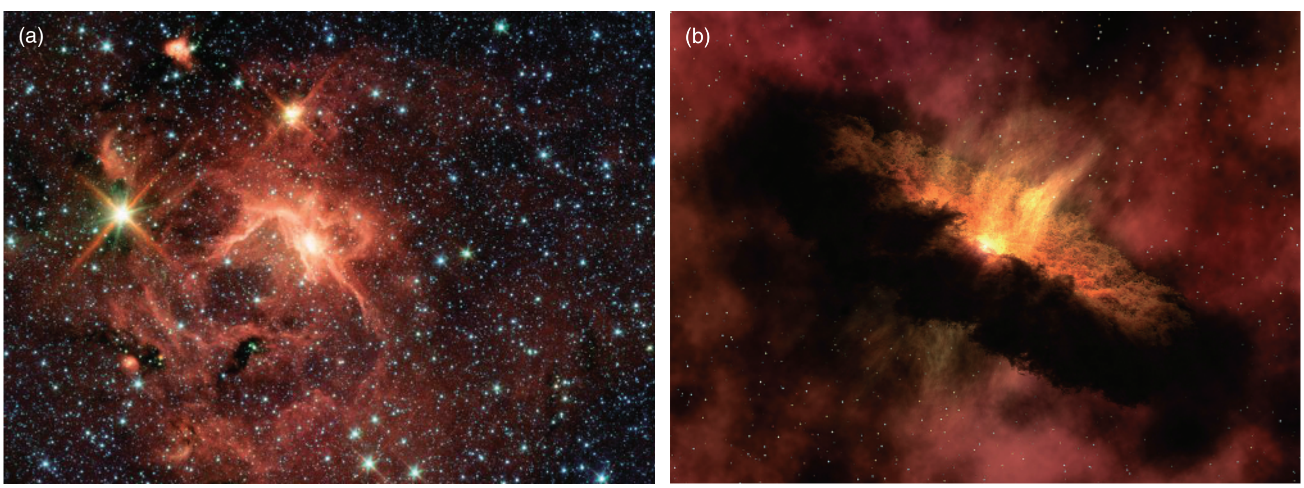


Figure 1.3 A new star forms in the constellation Centaurus. a) a bright new star (left side of the image) with a dust cloud around it. NASA/JPL-Caltech/ESO/ S. Kraus image. b) artist's impression of the new star. NASA/JPL-Caltech/R. Hurt (SSC) image.

Figure 1.4 The early Earth was hit by a Mars-sized asteroid, and the debris that was blasted into space quickly collected to form the Moon. NASA/JPL-Caltech image.

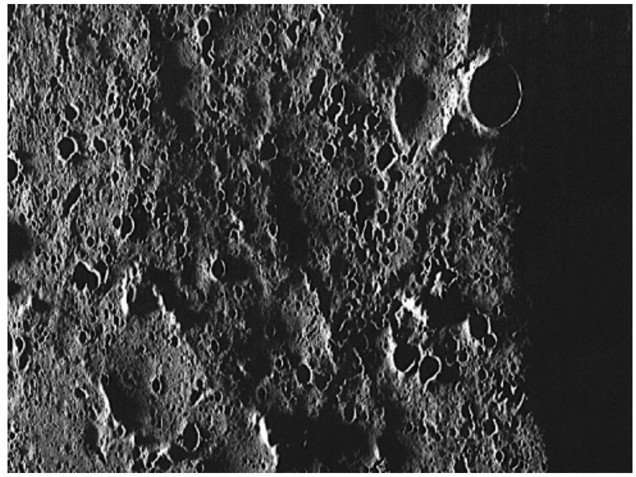


Figure 1.5 Image of the surface of Mercury: airless and lifeless. NASA image.

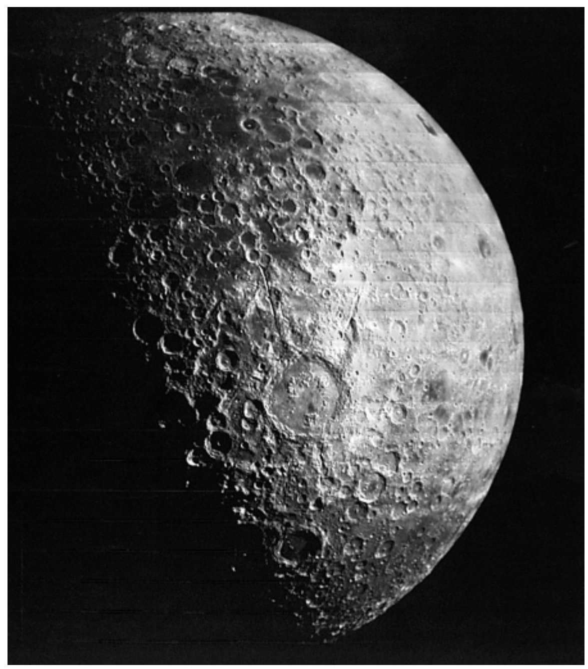


Figure 1.6 Image of the far side of the Moon: airless and lifeless. NASA image.

the similarity ended, and each inner planet has had its own later history.

Once a planet cools, conditions on its surface are largely controlled by its distance from the Sun and by any volcanic gases that erupt into its atmosphere from its interior. From this point onward, the geology of a planet greatly affects the chances that life might evolve on it.

Liquid water is vital for life as we know it, so surface temperature is perhaps the single most important feature of a young planet. Surface temperature is mainly determined by distance from the Sun: too far, and water freezes to ice; too close, and water evaporates to form water vapor.

But distance from the Sun is not the only factor that affects surface temperature. A planet with an early atmosphere that contained gases such as methane, carbon dioxide, and water vapor would trap solar radiation in the "greenhouse" effect, and would be warmer than an astronomer would predict just from its distance from the Sun.

In addition, distance from the Sun alone does not determine whether a planet has water, otherwise the Moon would have oceans like Earth's. The size of the planet is important, because gases escape into space from the weak gravitational field of a small planet. Gas molecules such as water vapor are lost faster from a small planet than from a larger one, and heavier gases as well as light ones are lost from a small planet. Thus Mars has only a thin atmosphere, and Mercury (Fig. 1.5) and the Moon (Fig. 1.6) have practically none.

Gases may be absorbed out of an atmosphere if they react chemically with the surface rocks of the planet. As they do so, they become part of the planet's geology, but may be released again if those rocks are melted in volcanic activity. But a small planet cools faster than a large one, so any volcanic activity quickly stops as its interior freezes. After that, no more eruptions can return or add gases to the atmosphere. Therefore, a small planet quickly evolves to have a very thin atmosphere or no atmosphere at all, and no chance of gaining one.

Volcanoes typically erupt large amounts of water vapor and CO_2, and these are both powerful greenhouse gases.

Earth would have been frozen for most of its history without volcanic CO_2 and water vapor in its atmosphere. Together they add perhaps 33°C to Earth's average temperature.

With these principles in mind, let's look at the prospects for life on other planets of our solar system. The brief story is that there is none. Both Mercury and the Moon had active volcanic eruptions early in their history, but they are small. They cooled quickly and are now solid throughout. Their atmospheric gases either escaped quickly to space from their weak gravitational fields or were blown off by major impacts. Today Mercury and the Moon are airless and lifeless.

Venus is larger than the Moon or Mercury, almost the same size as Earth. Volcanic rocks cover most of its surface. Like Earth, Venus has had a long and active geological history, with a continuing supply of volcanic gases for its atmosphere, and it has a strong gravitational field that can hold most gases. But Venus is closer to the Sun than Earth is, and the larger amount of solar radiation hitting the planet was trapped so effectively by water vapor and CO_2 that water molecules may never have been able to condense to become liquid water. Instead, water remained as vapor in the atmosphere until most of it was dissociated, broken up into hydrogen (H_2), which was lost to space, and oxygen (O_2), which was taken up chemically by reacting with hot surface rocks (Fig. 1.8).

Today Venus has a dense, massive atmosphere made largely of CO_2. Volcanic gases react in the atmosphere to make tiny droplets of sulfuric acid (H_2SO_4), forming thick clouds that hide the planetary surface. Water vapor has vanished completely. Although the sulfuric acid clouds reflect 80% of solar radiation, CO_2 traps the rest, so the surface temperature is about 450°C (850°F). We can be sure that there is no life on the grim surface of Venus under its toxic clouds.

Mars is much more interesting than Venus from a biological point of view. It is smaller than Earth (Fig. 1.7), and farther from the Sun. But it is large enough to have held on to a thin atmosphere, mainly composed of CO_2. Mars today is cold, dry, and windswept: dust storms sometimes cover half the planet.

No organic material can survive now on the surface of Mars. There is no liquid water, and the soil is highly oxidizing. But while Mars was still young, and was actively erupting volcanic gases from a hot interior, the planet may have had a thicker atmosphere with substantial amounts of water vapor. The crust still contains ice that could be set free as water if large impacts heated the surface rocks deeply enough to melt it, or if climatic changes were to melt it briefly.

So Mars does have water, but it is ice, frozen as part of the ice-caps, or under the surface sediment, where it is shielded from the sun. Ice can sublimate off the Martian surface, changing directly into water vapor. This blows around, sometimes being lost to space, sometimes freezing out again in the Martian winter.

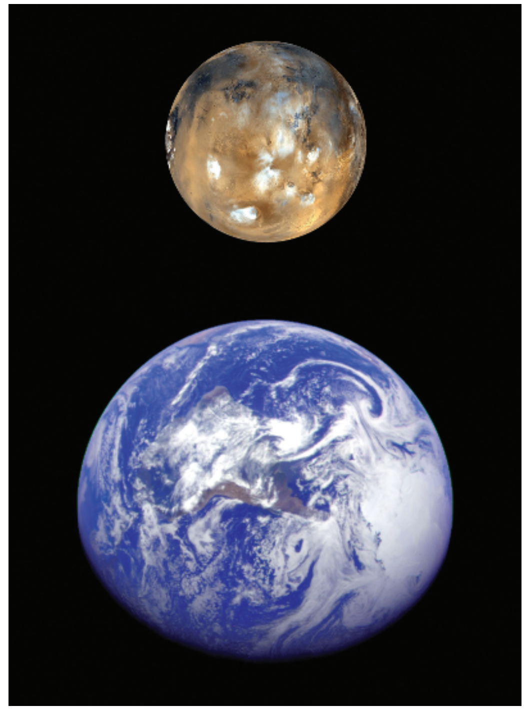


Figure 1.7 Earth and Mars at the same scale. North poles at left. NASA/JPL-Caltech image.

Mars occasionally had surface water in the distant past. Canyons, channels, and plains look as if they were shaped by huge floods (Fig. 1.9), and other features look like ancient sandbars, islands, and lake beds. Ancient craters on Mars, especially in the lowland plains, have been eroded by gullies, and sheets of sediment lap around and inside the old craters, sometimes reducing them to ghostly rims sticking out of the flat surface.

Mars was too small to sustain geological activity for long. As the little planet cooled, its volcanic activity stopped (Figs 1.8, 1.10). Its atmosphere was largely lost, blasted off by impacts, or by slow leakage to space, or by chemical reactions with the rocks and soil. There may never have been oceans, and even lakes would have lasted a very short time. The surface is a dry frozen waste, and likely has been for well over three billion years. Even floods generated by a large meteorite impact would drain away or evaporate very quickly: they could not have lasted long enough to sustain life. In short, Mars is a lifeless ice-ball, and has been for billions of years.

In 1996, researchers reported they had found fossil bacteria in a meteorite that originated on Mars. (It was blasted into space by an asteroid impact, and fell on to Earth's Antarctic ice cap after spending thousands of years in space.) The researchers suggested that the bacteria were Martian. By now the report has been discounted: the objects are not bacteria and they are not evidence for life on Mars.

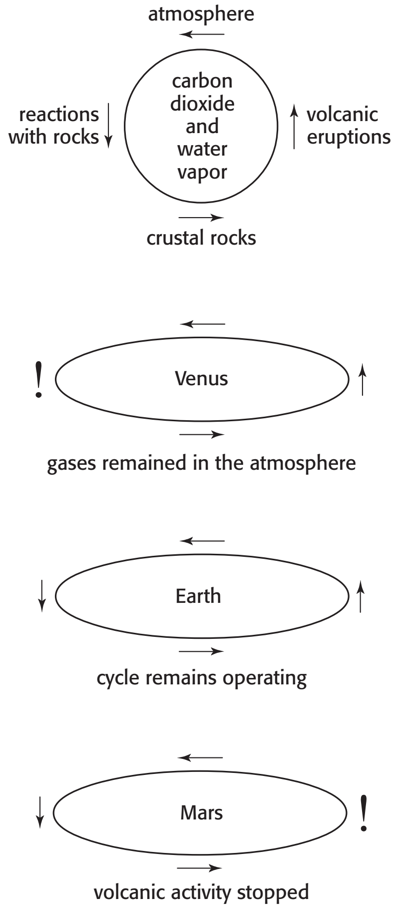


Figure 1.8 An idealized rocky planet, with surface reactions. Earth is like this, but Venus and Mars are not. This has made all the difference in their history. Mars is frozen and dead, Venus is hot and toxic. See text for details.

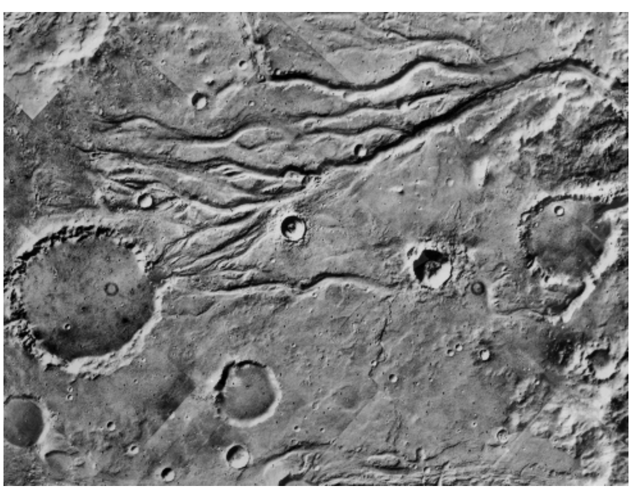


Figure 1.9 Ancient channels on the surface of Mars. NASA image.

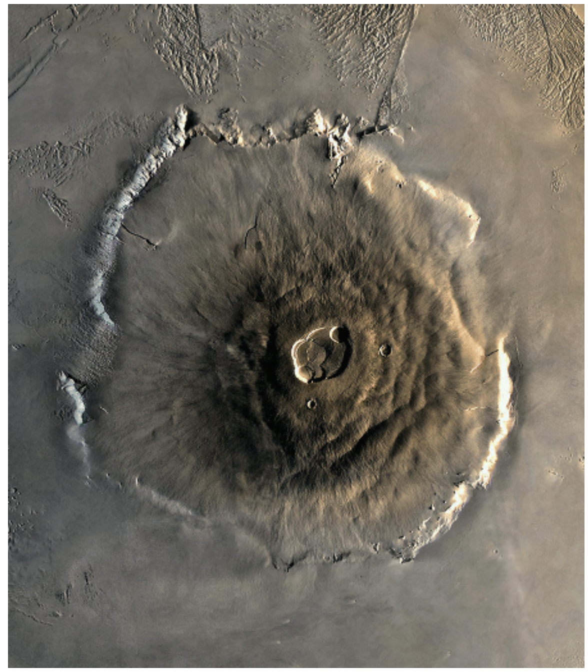


Figure 1.10 Olympus Mons, an enormous but long-extinct volcano on Mars, standing 27 km (17 miles) higher than the average crust of Mars, and over 600 km (370 miles) across at the base. NASA image.

The asteroid belt lies outside the orbit of Mars. Some asteroids have had a complex geological history, but here is no question of life in the asteroid belt now. Outside the asteroid belt, Jupiter and Saturn have ice-rich moons. But no planet or moon outside the orbit of Mars could trap enough solar radiation to form liquid water on its surface to provide the basis for life. Complex hydrocarbon compounds can accumulate and survive on asteroids, or in the atmospheres of the outer planets or on some of their satellites, but those bodies are frigid and lifeless.

Looking further afield, there is absolutely no evidence of life anywhere else in the universe. Many scientists argue that the universe is so vast that there must be other life out there, but that is speculation, not science. As we discover more planets around other stars, we find that many of them are in orbits that would make life impossible.

The Early Earth

So we return to Earth as the only known site of life. Gases released by eruptions and impacts formed a thick atmosphere around the early Earth, consisting mainly of CO_2 but with small amounts of nitrogen, water vapor, and sulfur gases. By about 4.4 billion years ago (4400 Ma or 4.4 Ga), Earth's surface was cool enough to have a solid crust, and liquid water accumulated on it to form oceans. Ocean water in turn helped to dissolve CO_2 out of the atmosphere and deposit it into carbonate rocks on the seafloor. This absorbed so much CO_2 that Earth did not develop runaway greenhouse heating as Venus did (Fig. 1.8). Large shallow oceans probably covered most of Earth, with a few crater rims and volcanoes sticking out as islands. The evidence for a cool watery Earth early in its history comes from a few zircon crystals that survived as recycled grains in later rocks. Some of the zircon crystals are dated close to 4.4 Ga.

We know from crater impacts and lunar samples that the Earth and Moon suffered a heavy late bombardment of asteroids around 3900 Ma, and the same event probably affected all the inner planets. Those catastrophic impacts must have destroyed almost all geological evidence of the early Earth's structure. Earth must have been hit by 100 or more giant asteroids and many smaller ones. At the same time, huge craters and basins filled with basalt lava were formed on the Moon (Fig. 1.11). The incoming asteroids seem to have been dislodged from their original orbits by changes in the orbits of Jupiter and perhaps Saturn as well, as those giant planets went through final gravitational adjustments in the complex dynamics of the solar system. The heat from the asteroid impacts probably melted the Earth's surface, boiled the ocean, and wiped out any life that might have evolved earlier. The life forms that were our ancestors could not have evolved and survived until after the last sterilizing impact.

Figure 1.11 The Late Heavy Bombardment hits the Moon (top), leaving scars that are still visible today (bottom). The effect on Earth would have been even greater because of Earth's greater mass. Image by Tim Wetherell of the Australian National University, and placed into Wikimedia.

As the great bombardment died away, small late impacts may have encouraged the evolution of life on Earth. All comets and a few meteorites carry organic molecules, and comets in particular are largely made of ice. These bodies could have delivered organic chemicals and water to Earth. But Earth already had water, and processes here on Earth also formed organic chemicals. Intense ultraviolet (UV) radiation from the young Sun acted on the atmosphere to form small amounts of very many gases. Most of these dissolved easily in water, and fell out in rain, making Earth's surface water rich in carbon compounds. The compounds included ammonia (NH_3), methane (CH_4), carbon monoxide (CO), ethane (C_2H_6), and formaldehyde (CH_2O). They could have formed at a rate of millions of tons a year. Nitrates built up in water as photochemical smog and nitric acid from lightning strikes also rained out. But the most important chemical of all may have been cyanide (HCN). It would have formed easily in the upper atmosphere from solar radiation and meteorite impact, then dissolved in raindrops. Today it is broken down almost at once by oxygen, but early in Earth's history it built up at low concentrations in lakes and oceans. Cyanide is a basic building block for more complex organic molecules such as amino acids and nucleic acid bases. Life probably evolved in chemical conditions that would kill us instantly!

We have a good idea of the conditions of the early Earth, and of the many possible organic molecules that might have been present in its atmosphere and ocean. But how did that result in the evolution of life? First we look at the biology and the laboratory experiments that help us to solve the question, and then we look at real world environments to help us to work out where it happened.

Life Exists in Cells

The simplest cell alive today is very complex: after all, its ancestors have evolved through many billions of generations. We must try to strip away these complexities as we wonder what the first living cell might have looked like and how it worked.

A living thing has several properties: it has organized structure, and the capacity to reproduce (replicate itself), and to store information; and it has behavior and energy flow (metabolism). Mineral crystals have the first two but not the last two.

A living thing has a boundary that separates it from the environment. It operates its own chemical reactions, and if it did not have a boundary those reactions would be unable to work: they would be diluted by outside water, or compromised by outside contaminants. So a living "cell" has some sort of protective membrane around it.

A cell, like a computer, has hardware, software, and a protective case, all working well together. The case, or **cell membrane**, is made from molecules called **lipids**. The software that contains the information for running a cell is coded on **nucleic acids** (DNA and RNA), which use a four-character code rather than the two-character code (0 and 1) that our computers all use. The hardware consists largely of **proteins**, long molecules made from strings of **amino acids**. All those components had to become parts of a functioning organism.

A living thing can grow, and it can **replicate**, that is, it can make another structure just like itself. Both processes require complex chemistry. Growth and replication use materials that must be brought in from outside, through the cell wall.

A living thing interacts with its environment in an active way: it has **behavior**. The simplest behavior is the chemical flow of substances in and out of the cell, which can be turned on and off. The chemical flow will change the immediate environment, and the presence or absence of the desired chemicals will decide whether the cell turns the flow on or off. Temperature and other outside conditions also affect the behavior of even the simplest cell.

The chemical activity of the cell includes an energy flow that is called **metabolism** in living things. The cell must make molecules from simpler precursors, or break down complex molecules into simpler ones. If a cell grows or reproduces, it builds complex organic molecules, and those reactions need energy. The cell obtains that energy from outside, in the form of radiation or "food" molecules that it breaks down.

These attributes of a living cell are not different things: they are all intertwined, connected with gathering and processing energy and material into new chemical compounds (tissues), and continuing those processes into new cells. Any reconstruction of the evolution of life, as opposed to its creation by a Divine Being, must include a period of time during which lifeless molecules evolved the characters listed above and thereby became living. The phrase for this process is **chemical evolution**. We have to be able to argue that every step in the process could reasonably have happened on the early Earth in a natural, spontaneous way. It's easy to see that a protocell could grow effectively, given the right conditions. The critical turning point that defines life comes when relatively accurate replication evolves.

Even with a time machine, it would be very difficult to pick out the first living thing from the mass of growing organic blobs that must have surrounded it. But that cell survived and replicated accurately, and as time went by, its descendant cells that were more efficient remained alive and replicated, while those that were less efficient died or replicated more slowly. So as living things slowly emerged, chemical evolution slowly changed into *biological* evolution as we understand it today, subject to natural selection and extinction. Some lines of cells flourished, others became extinct. So living cells today do not exactly have the same genetic and biochemical machinery their ancestors had: they have long had major upgrades of their original software.

That brings one other concept into our discussion: *improvement* or *progress*. There is no question that the simplest living cells today are more efficient than their distant ancestors. Arguments rage about the politically correct word to use to describe this. The fossil record shows many examples of improved performance that can be analyzed mechanically. Living horses and living humans run far more efficiently, living whales swim more efficiently, and living birds fly more efficiently than their ancestors did. No doubt similar trends have occurred in physiology, biochemistry, reproduction, and so on. I can't think of a better word to describe this than **progress**.

We turn now to experiments that help us to see how life evolved from nonliving chemicals. The only life we know is on Earth, so we are testing the hypothesis that ingredients for the first cells were available on Earth, and that the first cells could have evolved along reasonable pathways.

The first stages in reconstructing the evolution of life were experiments in making the different necessary chemical components in plausible conditions. Now with success in that first stage, research has moved on to find how the components were successfully assembled into working units, getting closer to objects we might call "protocells".

Making Organic Molecules

In 1953 Stanley Miller, a young graduate student at the University of Chicago, passed energy (electric sparks) through a mixture of hydrogen, ammonia, and methane in an attempt to simulate likely conditions on the early Earth (Fig. 1.12). Any chemical products fell out into a protected flask. Among these products, which included cyanide and formaldehyde, were amino acids. This result was surprising at the time because amino acids are complex compounds, and are also vital components of all living cells.

The experiment that Miller published used a rather unlikely mixture of starting gases, but he also did a number of other experiments that gave similar results. Some were not published at the time, but Miller stored all his lab notes and experimental vials. When they were discovered after his death and analysed with 21st century techniques, it turns out that the best results came when Miller added volcanic gases to his mixtures (Parker et al. 2011).

It is now clear that almost all the amino acids found in living cells today could have formed naturally on the early Earth, from a wide range of ingredients, over a wide range of conditions. They form readily from mixtures that include the gases of Earth's early atmosphere. The same amino acids that form most easily in laboratory experiments are also the most common in living cells today. The only major condition is that amino acids do not form if oxygen is present.

Miller's experiments made amino acids in sterile glass flasks. But in later experiments, it was found that amino acids form even more easily on the surfaces of clay particles. Clay minerals are abundant in nature, have a long linear crystal structure, and are very good at attracting and adsorbing organic substances: cat litter is made from a natural clay and works on this principle.

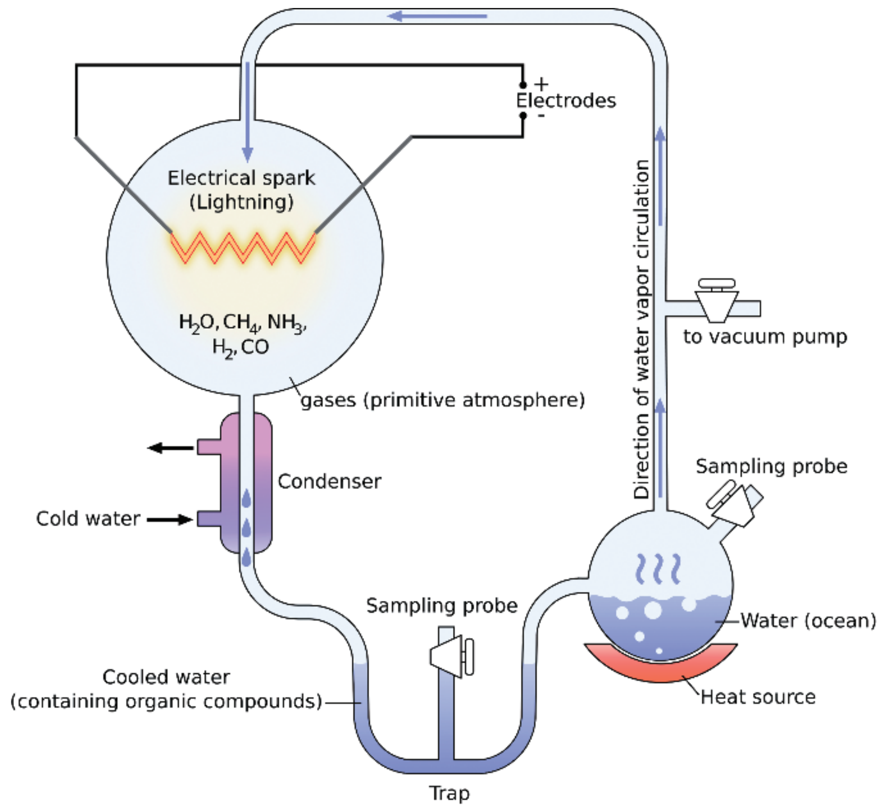


Figure 1.12 Stanley Miller's classic 1953 experiment, designed to simulate conditions on the early Earth. An atmosphere largely of water vapor, methane, and ammonia was subjected to lightning discharges. The reaction products cooled, condensed, and rained out to collect in the ocean. Those reaction products included amino acids. Diagram by Yassine Mrabet, and placed into Wikimedia.

People used to talk about "primordial soup", with the idea that interesting organic molecules would have been present throughout Earth's oceans. Everyone recognizes now that for the later stages of complex organic chemistry, organic molecules need to be concentrated, which allows them to react faster and more efficiently. Life may have begun in a rather unusual local environment.

For example, linking sequences of amino acid molecules into chains to form protein like molecules involves the loss of water, so scientists have tried evaporation experiments in simulated early Earth conditions. Four natural concentration mechanisms are evaporation; freezing; being enclosed inside membranes in scums, droplets, or bubbles; and concentration by being absorbed on to the surfaces of mineral grains. High temperatures help evaporation, but organic molecules tend to break down if they are heated too much. The longer the molecule, the more vulnerable it is to heat damage. However, experiments at low temperature form large molecules rather well. As water freezes into ice, other chemicals present are greatly concentrated. If they react to form larger organic molecules, the new molecules survive well.

Nucleic acids (**RNA** and **DNA**) have structures made of nucleic-acid bases or **nucleobases**; sugars; and phosphates. All the nucleobases have now been made in reasonable laboratory experiments. Sugars form in experiments that simulate water flow from hot springs over clay beds. Sugars and nucleobases could have formed in reactions powered by lightning. Naturally occurring phosphate minerals are associated with volcanic activity. Thus all the ingredients for nucleic acids were present on the early Earth, and the cell fuel ATP could also have formed easily.

Linking sugars, phosphates, and nucleobases to form fragments of nucleic acid called **nucleotides** also involves the loss of water molecules, and the phosphates themselves can act as catalysts here. Long nucleotides form much more easily on phosphate or clay surfaces than they do in suspension in water.

Many organic membranes are made of sheets of molecules called **lipids**. A lipid molecule has one end that attracts water and one end that repels water. Lipid molecules line up naturally with heads and tails always facing in opposite directions (Fig. 1.13); a bilayer sheet of lipid molecules therefore repels water. If a single or a double

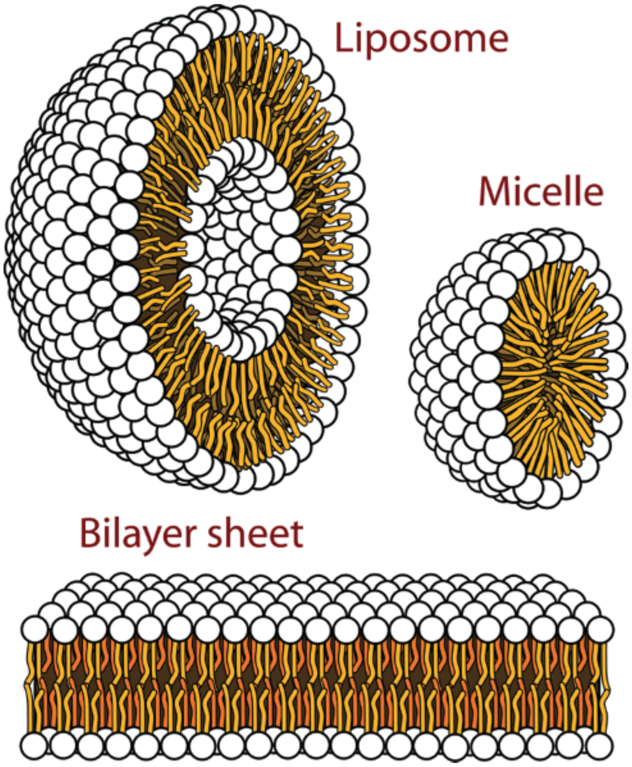


Figure 1.13 The different shapes that lipid layers can form. Liposomes are also called vesicles. Vesicles can enclose mixtures of chemicals in a central cavity, and are very important in origin-of-life experiments. Image by Lady of Hats, Mariana Ruiz Villarreal, and placed into Wikimedia.

sheet of lipids happens to fold around to meet itself, it forms globular waterproof membranes (micelles) or hollow pills (liposomes or **vesicles**). Such shapes form spontaneously in lipid mixtures. Whipping up an egg in the kitchen produces lipid globules as the contents are frothed around. In the real world, lipid foams can form in the scum on wave surfaces (Fig. 1.14).

A breakthrough came when David Deamer's research group found that fatty acid molecules occur in the Murchison meteorite (Fig. 1.15), which fell in Australia in 1969. Those fatty acids could be extracted and formed into lipid vesicles by drying them out and then rewetting them (Fig. 1.16). Vesicles can also form from mixtures of molecules that would have been present on the early Earth. Deamer shook mixtures of lipids, amino acids and nucleic acids, and found that they formed spontaneously into many vesicles with organic molecules trapped inside them. They became tiny reaction chambers, inside which complex chemical changes could and did happen.

Nature has done experiments on making organic molecules. The meteorites and comets that strike Earth often carry organic compounds, and we can analyze them

Figure 1.14 Sea foam, formed by waves on a South Australian beach. The dog is for scale. Photo taken by Bahudhara, and placed into Wikimedia.

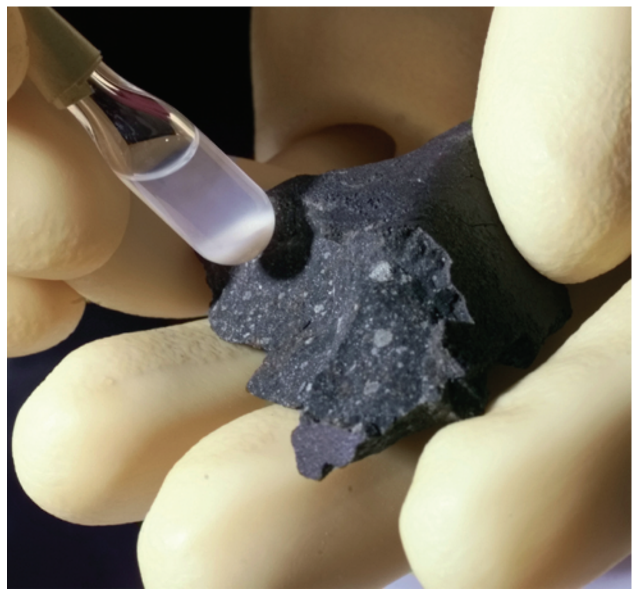


Figure 1.15 A fragment of the Murchison meteorite yielded fatty acids that readily form into vesicles. Image from the US Department of Energy.

knowing that they formed somewhere in space. The most common organic compounds in meteorites are also the most abundant in experiments that try to simulate chemistry in space. Many forms of amino acids, sugars, and nucleobases are found in meteorites, and so are fatty acids that easily form lipid membranes. Thousands of different organic compounds could have been supplied to the early Earth (Schmitt-Kopplin et al. 2010). We do not know how much organic matter was formed in natural processes on Earth and how much was delivered on comets and

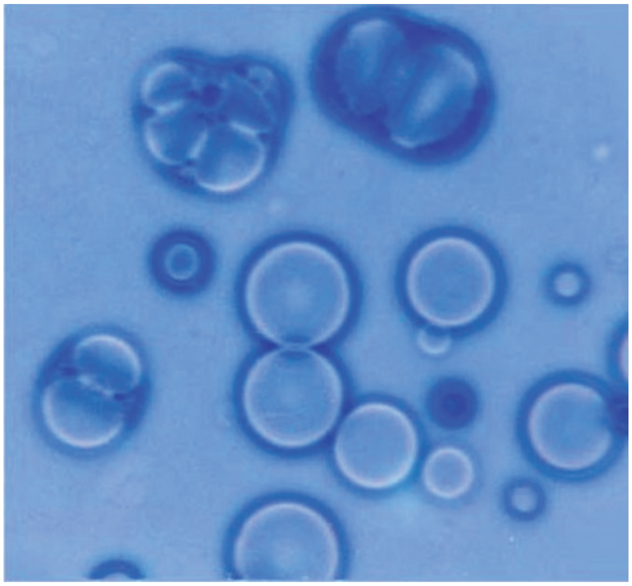


Figure 1.16 Lipid vesicles made in David Deamer's laboratory from fatty acids extracted from the Murchison meteorite. NASA image.

meteorites before and after the Late Bombardment. Either way, the right materials were present on the early Earth to encourage further reactions.

Toward the First Living Cell

How did basic organic molecules evolve into a cell that could reproduce itself? Deamer's early experiments began a new style of prebiotic experiments, using vesicles rather than test-tubes. After all, vesicles with cell-like contents could have formed in great numbers as waves thrashed around lipids on water surfaces (Fig. 1.14), or as lipid scums washed up on a muddy shore with clays in the water, or in the turbulent convection in and around hot springs. These vesicles would have had very variable contents (some with amino acids, primitive forms of nucleic acid, and so on). The "best" ones would have operated chemical reactions much more efficiently than the "worst". They would have done this because they had "better" nucleic acids, coded to produce "better" sets of protein enzymes to run efficient reactions.

Researchers have now found that vesicles can form 100 times as fast as usual if clay is added to the experimental mixtures. Some vesicles can take in substances from outside, through the lipid walls, and use them to build new walls and new contents: that is, they can grow. Irene Chen found that an active vesicle can "steal" (attract and absorb) part of the membrane from a less active neighbor and use it to grow! Vesicles can display a kind of "reproduction" in the sense that a large vesicle may divide into two, each keeping some of the original vesicle contents (Chen et al. 2004, Chen 2009).

So we can imagine some watery environment where vesicles were growing and dividing more and more efficiently as their nucleic acids, their proteins, and their vesicle walls came to work well together.

In living cells today, information for making proteins is coded on long sequences of nucleic acid. The molecules of DNA that specify these protein structures are difficult to replicate, and replication requires many proteins to act as enzymes to catalyze the reactions. In living cells today, protein synthesis and DNA replication are interwoven: they depend on one another. So how could DNA and proteins have been formed independently, then evolved to depend on each other?

The answer lies with the simpler nucleic acid, RNA. Some RNA sequences called **ribozymes** can act as enzymes and make more RNA, even when no proteins are present. Other RNA sequences speed up the assembly of proteins. Perhaps the first living things were efficient vesicles that contained ribozymes with the right structure to replicate themselves accurately. (Such ribozymes have come to be called **naked genes**, but in reality they were inside vesicles.) Ribozymes would also have coded for the proteins needed to grow the vesicle and divide. In theory, RNA ribozymes on the early Earth could have replicated themselves with minimal proteins, in vesicles that we can now call **protocells**. Increasingly successful protocells would very quickly have outcompeted their neighbors. At some point, a successful protocell became the ancestor of all later life on Earth. The scenario that begins with ribozymes in an RNA world is currently the best hypothesis for the origin of life on Earth.

Where Did Life Evolve?

Most theories of the origin of life suggest surface or shoreline habitats in lakes, lagoons, or oceans. But it's unlikely that life evolved in the open sea. Complex organic molecules are vulnerable to damage from the sodium and chlorine in seawater. Most likely life evolved in lakes, or in seashore lagoons that were well supplied with river water. We have come to think of lagoons as tropical: the very name conjures up blue water and palm trees. Warm temperatures promote chemical reactions, and an early tropical island would most likely have been volcanic and therefore liable to have interesting minerals. But RNA bases are increasingly unstable as temperatures rise: normal tropical water, at 25°C, is about as warm at it could be for the origin of life.

So perhaps lakes or lagoons on cold volcanic islands were the best environments favoring organic reactions on the early Earth. In the laboratory, cyanide and formaldehyde reactions occur readily in half-frozen mixtures. Volcanic eruptions often generate lightning storms (Fig. 1.17), so eruptions, lightning, fresh clays, and near-freezing temperatures (ice, snow, hailstones) could all have been present

Figure 1.17 Volcanic lightning in an eruption cloud, at Rinjani volcano in Indonesia, 1995. Photograph by Oliver Spalt and placed into Wikimedia.

Figure 1.18 A volcanic island set in a cold climate: Onekotan, in the Kurile Islands on the Russian East coast. The southern volcano, on an island in a large crater, is Krenitzyn Peak. Image from NASA Earth Observatory.

on the shore of a cold volcanic island (Fig. 1.18). Note that if this environment is the correct one, there had to have been land and sea when life evolved: fresh water can only occur on Earth if it is physically separated from the ocean.

Solar radiation or lightning are likely energy sources for the reactions leading toward life. But deep in the oceans are places where intense geothermal heating generates hot springs on the sea floor. Most of these lie on the mid ocean ridges, long underwater rifts where the sea floor is tearing apart and forming new oceanic crust. Enormous quantities of heat are released in the process, much of it through hot water vents, and myriads of bacteria flourish in the hot water. Perhaps life began nowhere near the ocean surface, but deep below it, at these **hydrothermal vents** (Fig. 1.19).

Laboratory experiments have implied that amino acids and other important molecules can form in such conditions, even linking into short protein-like molecules, and currently the deep-sea hypothesis is popular. But if life evolved by way of naked genes, then it did not do so in hot springs. RNA and DNA are unstable at such high temperatures. Naked genes could not have existed (for long enough) in hot springs.

The deep-sea hypothesis, even though it looks unlikely (to me), has led to speculation that life might have evolved deep under the surface layers of other planets or satellites. (For example, Jupiter's moon Europa probably has liquid water under its icy crust, and Saturn's moon Enceladus has been seen to erupt water vapor "geysers".) The speculation helps to generate money for NASA's planetary probes. But the internal energy of such planets and moons is very low,

Figure 1.19 Hydrothermal vents on the Pacific Ocean floor. Image from NOAA.

and water-borne organic reactions are much less likely to work deep under the icy crust of Europa or Enceladus than in Earth's oceans. In any case, the under-ice oceans of icy moons are salty (that's how they were detected), so an origin of life is very unlikely in such environments.

Energy Sources for the First Life

Living things use energy. Much of biology consists of studying metabolism and ecology: how living things acquire and use the energy they need to grow and reproduce.

As we have seen, reactions powered by solar power, volcanic heat, lightning, or delivery from outside, built up a reservoir of simple organic chemicals on the early Earth. Protocells likely evolved in a watery environment that contained easily available chemical energy in naturally formed organic molecules such as ATP, amino acids, sugars, and other organic compounds.

So the first protocells had energy, fuel for cell growth and replication. But as they became more numerous and more effective in attracting and using organic molecules, there must have come a time when demand for energy exceeded supply. As simple organic molecules became scarcer and scarcer, protocells encountered the world's first energy crisis. This crisis would have happened first in those environments where protocells were most successful and abundant.

The energy that humans use so carelessly today comes from only two sources: solar energy and geothermal energy. Solar energy is in the form of direct radiation (heat and light); or as indirect energy, since solar energy powers wind and ocean currents, and evaporates water vapor that eventually falls as rain that runs hydroelectric plants. Even more indirect solar energy came from the sunlight that powered plant growth in the past, now found as fossil fuels in the earth: peat, coal, oil and gas. Geothermal energy can be tapped by drilling into steam vents or hot rocks, or by mining and concentrating radioactive minerals for fuel in nuclear power plants. Of the two sources, solar energy is by far the largest and easiest to manage.

Early cells found two very different solutions to their energy crisis that can still be seen among living organisms nearly 4 billion years later. Both depend on harnessing solar energy, but they occur in two very different kinds of organisms, using two very different processes.

Living organisms take in outside energy in two ways: **heterotrophy** and **autotrophy**. Heterotrophs obtain their metabolic energy by breaking down organic molecules they obtain from the environment: hummingbirds sip nectar and humans eat doughnuts. Heterotrophs do not pay the cost of building the organic molecules. They simply have to operate the reactions that break them down. But they must live where they can find "food" molecules. The first cells, living on the organic molecules around them, were heterotrophs.

Autotrophs do not need food molecules from outside: they make them inside the cell, paying the cost of building them by absorbing energy from outside. Autotrophy was evolved by some early cells, but not by all of them.

Heterotrophy

The simplest reaction used by cells to break down organic molecules is **fermentation**, to break down sugars such as glucose. This is what early heterotrophs must have done. Glucose is often called the universal cellular fuel for living organisms, and it was probably the most abundant sugar available on the early Earth. [Today, humans use fermenting microorganisms to produce beer, cheese, vinegar, wine, tea, and yogurt, and to break down much of our sewage.]

As heterotrophs used up the molecules that were easiest to break down, there would have been intense competition among them to break down more complex ones. One can imagine a huge advantage for cells that evolved enzymes to break down molecules that their competitors could not use. New sets of fermentation reactions would quickly have evolved, and different lineages of heterotrophic cells would have come to be specialists in their chemistry.

In becoming more efficient heterotrophs, some early cells found a way to import energy to make their internal chemistry run faster at no extra cost. In the last ten years, microbiologists have found that billions of heterotrophic microbes living in the world's shallow waters, in seas and lakes, and even in the ice around Antarctica, can absorb light energy and use it to help their internal chemical reactions. The molecules that can absorb light in this fashion are called **rhodopsins**.

We and many other creatures now use rhodopsins in our eye cells as light sensors. Light hitting a rhodopsin molecule activates it, and after a cascade of reactions, a nerve impulse is sent to the brain. Rhodopsins are the universal molecules in biological visual systems, allowing bacteria and fungi as well as humans to detect and react to light.

But the first rhodopsin molecules probably did something else. Rhodopsin is triggered by light to add electric charges to protons, and those protons can then be taken off to power chemical reactions inside the cell. Light-powered chemistry thus gives an advantage to rhodopsin-bearing heterotrophs over their competitors. Much of the biology in the ocean's surface waters is powered by rhodopsin reactions, and we knew nothing about them ten years ago! This system is called **phototrophy** ("feeding by light") because the rhodopsin reactions help to break down molecules, but do not build them up. Rhodopsin reactions aid heterotrophs, not autotrophs.

The first rhodopsin systems probably evolved only once, in some lucky mutant cell. The genes that code for rhodopsin are not large, and they seem to have passed easily from one cell to another, so that now, after billions of years, many different lineages of heterotrophic cells now use rhodopsin to save energy. Of course, rhodopsin is useful only in water that is shallow enough to receive sunlight. Heterotrophs living in dark environments must run at lower energy levels.

Autotrophy

Autotrophs generate their own energy, but in two completely different ways. Some extract chemical energy from inorganic molecules (**lithotrophy**), while others gain energy by trapping solar radiation (**photosynthesis**).

Lithotrophy can occur when a microorganism rips an oxygen molecule off one inorganic compound and transfers it to another, making an energy profit in the process. That energy is then used to build organic food molecules. For example, microorganisms called **methanogens** gain energy from lithotrophy by breaking up carbon dioxide and transferring the oxygen to hydrogen, forming water and methane as by-products:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + \text{energy}$$

Methanogens are as different from true bacteria as bacteria are from us, and are part of a special group of microorganisms, the Archaea. Since carbon dioxide and hydrogen would have been available in the early ocean, it is reasonable to suggest that this reaction could have been used by very early cells. Indeed, based on their molecular genetics, Archaea were among the first living things on Earth.

If lithotrophy evolved very early, it may have been the first time (but not the last) that living things modified Earth's chemistry and climate. By replacing the greenhouse gas carbon dioxide with the even more powerful greenhouse gas methane, the activity of methanogens might have warmed the early Earth (Chapter 2).

Photosynthesis is simple in concept: energy from light is absorbed into specific molecules called **chlorophylls**. The process is biochemically more complex than lithotrophy or phototrophy. Chlorophylls (and the genes that code for making them) seem to have evolved only once.

The evolution of photosynthesis produced major ecological changes on Earth. Light energy trapped by chlorophyll was used to build more *biomass* (biological substance), giving photosynthetic cells an energy store, a buffer against times of low food supply, that could be used when needed. It's easy to see how such cells could come to depend almost entirely on photosynthesis for energy. In doing so, they did not have to compete directly with heterotrophs. In addition, as photosynthesizers died, and their cell contents were released into the environment, they inadvertently provided a dramatic new source of nutrition for heterotrophs. Photosynthesis greatly increased the energy flow in Earth's biological systems, and for the first time considerable amounts of energy were being transferred from organism to organism, in Earth's first true ecosystem.

The earliest photosynthetic cells probably used hydrogen from H2 or H2S. For example, the reaction

$$H_2S + CO_2 + \text{light} \rightarrow (CH_2O) + 2\ S$$

released sulfur into the environment as a by-product of photosynthesis. Later, photosynthetic bacteria began to break up the strong hydrogen bonds of the water molecule. Bacteria that successfully broke down H_2O rather than H_2S, like this:

$$2H_2O + CO_2 + \text{light} \rightarrow (CH_2O) + 2\ O$$

immediately gained access to a much more plentiful resource. There was a penalty, however. The waste product of H_2S photosynthesis is sulfur (S), which is easily disposed of. The waste product of H_2O photosynthesis is an oxygen radical, monatomic oxygen (O), which is a deadly poison to a cell because it can break down vital organic molecules by oxidizing them. Even for humans, it is dangerous to breathe pure oxygen or ozone-polluted air for long periods.

Cells needed a natural antidote to this oxygen poison before they could operate the new photosynthesis consistently inside their cells. **Cyanobacteria** were the organisms that made the first breakthrough to oxygen photosynthesis using water. A lucky mutation allowed them to make a powerful antioxidant enzyme called **superoxide dismutase** to prevent O from damaging them: essentially, the enzyme packaged up the O into less dangerous O2 that was ejected out of the cell wall into the environment.

From then on, we can imagine early communities of microorganisms made up of autotrophs and heterotrophs, each group evolving improved ways of gathering or making food molecules.

Photosynthesizers need nutrients such as phosphorus and nitrogen to build up their cells, as well as light and CO_2. In most habitats, the nutrient supply varies with the seasons, as winds and currents change during the year. Light, too, varies with the seasons, especially in high latitudes. Since light is required for photosynthesis, great seasonal fluctuations in the primary productivity of the natural world began with photosynthesis. Seasonal cycles still dominate our modern world, among wild creatures and in agriculture and fisheries.

We can now envisage a world with a considerable biological energy budget and large populations of microorganisms: Archaea, photosynthetic bacteria, and heterotrophic bacteria. So there is at least a chance that a paleontologist might find evidence of very early life as fossils in the rock record. In Chapter 2 we shall look at geology, rocks, and fossils, instead of relying on reasonable but speculative arguments about Earth's early history and life.

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Questions for Thought, Study, and Discussion

1. It is clear that after Earth had cooled, comets and meteorites added important ingredients to its surface: ice (= water), and a great variety of organic molecules. Many scientists think that this "late accretion" gave Earth the ingredients for the formation of life. However, the same ingredients must have been added to Mars and Venus and the Moon also, with no sign that they ever evolved life. So why did Earth evolve life while the others did not?
2. Many movies have portrayed extinct animals. Suppose I said to you that none of the portrayals were scientific. Give a careful response to this assertion.
3. Where on Earth did life first evolve? When you decide where it was, give a careful summary of the evidence that helped you to come to your answer.