From Soup to Cells—the Origin of Life

Evolution encompasses a wide range of phenomena: from the emergence of major lineages, to mass extinctions, to the evolution of antibiotic resistant bacteria in hospitals today. However, within the field of evolutionary biology, the origin of life is of special interest because it addresses the fundamental question of where we (and all living things) came from.

Many lines of evidence help illuminate the origin of life: ancient fossils, radiometric dating, the phylogenetics and chemistry of modern organisms, and even experiments. However, since new evidence is constantly being discovered, hypotheses about how life originated may change or be modified. It's important to keep in mind that changes to these hypotheses are a normal part of the process of science and that they do not represent a change in the basis of evolutionary theory.

When did life originate?
Evidence suggests that life first evolved around 3.5 billion years ago. This evidence takes the form of microfossils (fossils too small to be seen without the aid of a microscope) and ancient rock structures in South Africa and Australia called stromatolites. Stromatolites are produced by microbes (mainly photosynthesizing cyanobacteria) that form thin microbial films which trap mud; over time, layers of these mud/microbe mats can build up into a layered rock structure — the stromatolite.

Stromatolites are still produced by microbes today. These modern stromatolites are remarkably similar to the ancient stromatolites which provide evidence of some of the earliest life on Earth. Modern and ancient stromatolites have similar shapes and, when seen in cross section, both show the same fine layering produced by thin bacterial sheets. Microfossils of ancient cyanobacteria can sometimes be identified within these layers.

Although it's possible that life may have originated earlier, we are unlikely to find fossil cells older than 3.5 billion years, because the few sedimentary rocks that date back earlier than this have been reshaped too much by geological processes to show any intact fossil remains. In addition, the oldest identified rocks on Earth are only slightly older than 3.85 billion years, and these rocks are both very
rare and heavily altered by heat and pressure from tectonic activity. Thus, even if early organisms left some imprint in such ancient rocks, the evidence may now be gone. Not only that, but the young Earth probably experienced numerous large impacts during the heavy bombardment, which ended between about 3.8 and 4.0 billion years ago. If any life had arisen before the heavy bombardment ended, these impacts would have extinguished it and sterilized our planet. We cannot know when the last sterilizing impact occurred. It might have been as early as 4.1-4.2 billion years ago or as late as about 3.9 billion years ago.

**Where did life originate?**
Scientists have explored several possible locations for the origin of life, but perhaps it is best to begin by considering locales that we can probably rule out.

It seems unlikely that life arose on the land surface. The Earth’s early atmosphere contained no molecular oxygen, which means our planet could not have a protective layer of ozone. Ozone is a form of oxygen produced in the upper atmosphere by interactions between oxygen and ultraviolet light from the sun, producing O₃ instead of the familiar O₂ that we breathe. Today, ozone shields the Earth’s surface from the Sun’s dangerous ultraviolet radiation. Before the ozone layer existed, any surface life would have been exposed to very high levels of this radiation. While we can’t rule out the possibility that life might have arisen in such an environment—indeed, some organisms today can survive high-radiation conditions— the environment would have been much more hospitable underwater or in rocks beneath the surface.

A few decades ago, most scientists favored shallow ponds as the first home for life, largely because a famous experiment of the time (called the Miller-Urey experiment) suggested that these ponds might have been full of organic compounds (called the “Primordial Soup”). As these ponds evaporated, the compounds would have become more concentrated, making it easier for them to combine into more complex molecules that could lead to life. However, more recent experiments have not supported this scenario and have suggested that shallow ponds would have lacked a source of chemical energy sufficient to support the origin of life.

However, recently some scientists have narrowed in on the hypothesis that life originated near a deep sea hydrothermal vents ore in hot springs. The chemicals found in these vents and the energy they provide could have fueled many of the chemical reactions necessary for the evolution of life. Of course, we cannot rule out the possibility of that life originated elsewhere, such as within rocks, and adapted readily to these hot water environments. For example, the last major impact of the heavy bombardment might have raised global temperatures so only organisms that had already adapted to hot water environments could survive.

We have at least some reason to favor deep-sea vents over surface hot springs as the earlier home for life. Smaller impacts were more common than larger ones during the heavy bombardment, so partial vaporization of the oceans should have been more common than complete vaporization. No place on Earth was completely safe, but the deep ocean was clearly safer than springs at or near the surface. Furthermore, using the DNA sequences of modern organisms, biologists have tentatively traced the most recent common ancestor of all life to an aquatic microorganism that lived in extremely high temperatures — a likely candidate for a hydrothermal vent inhabitant! Although several lines of evidence are consistent with the hypothesis that life began near deep sea vents, it is far from certain: the investigation continues and may eventually point towards a different site for the origin of life.
Origins and DNA evidence

Such comparisons of DNA sequences are what led biologists to the conclusion that life can be divided into 3 major domains: Bacteria, Archaea, and Eukarya. Through more detailed analysis, biologists have mapped out relationships among many types of organisms in the tree of life. Each of the 3 domains represents one major branch of the tree, with each domain branching further in many other ways. The tree of life does not tell us when different organisms evolved; rather, it shows how closely or distantly related they are. Note also that we do not expect any living organism to be much like the common ancestor of all life on Earth. All modern species have presumably evolved significantly over time, so even the "simplest" bacterium must be quite complex compared to the common ancestor. Nevertheless, organisms on branches that emerge closer to the "root" of the tree must represent the descendants of organisms that branched off from other parts of the tree at earlier times in evolutionary history. It also seems likely that all three domains arose quite early- perhaps more than 3.5 billion years ago- and that nearly all the known branches split off soon after that.

Despite the uncertainty in the branching order, it appears that many organisms on branches closest to the root are extremophiles such those living near deep-sea volcanic vents (black smokers) or in hot springs like those in Yellowstone. These organisms are adapted to life in hot water (making them hyperthermophiles) and use chemical energy rather than photosynthesis to fuel their metabolism. Thus, it appears the common ancestor of all modern life on Earth resembled those extremophiles more closely than it did any other organisms living today.

Biologists use the DNA sequences of modern organisms to reconstruct the tree of life and to figure out the likely characteristics of the most recent common ancestor of all living things — the "trunk" of the tree of life. In fact, according to some hypotheses, this "most recent common ancestor" may actually be a set of organisms that lived at the same time and were able to swap genes easily. In either case, reconstructing the early branches on the tree of life tells us that this ancestor (or set of ancestors) probably used DNA as its genetic material and performed complex chemical reactions. But what came before it? We know that this last common ancestor must have had ancestors of its own - a long line of forebears forming the root of the tree of life - but to learn about them, we must turn to other lines of evidence.
How did life originate?

Living things (even ancient organisms like bacteria) are enormously complex. However, all this complexity did not leap fully-formed from the primordial soup. Instead life almost certainly originated in a series of small steps, each building upon the complexity that evolved previously:

1. **Simple organic molecules were formed.**
   Simple organic molecules, similar to the nucleotide shown below, are the building blocks of life and must have been involved in its origin. RNA and DNA molecules — the genetic material for all life — are just long chains of simple nucleotides.

   ![a nucleotide, composed of carbon, hydrogen, nitrogen, oxygen and phosphorus atoms](image)

2. **Replicating molecules evolved and began to undergo natural selection.**
   All living things reproduce, copying their genetic material and passing it on to their offspring. Thus, the ability to copy the molecules that encode genetic information is a key step in the origin of life — without it, life could not exist. This ability probably first evolved in the form of an RNA self-replicator — an RNA molecule that could copy itself.

   ![RNA molecules form from chains of nucleotides](image)

   Many biologists hypothesize that this step led to an "RNA world" in which RNA did many jobs, storing genetic information, copying itself, and performing basic metabolic functions. Today, these jobs are performed by many different sorts of molecules (DNA, RNA, and proteins, mostly), but in the RNA world, RNA did it all.

   Self-replication opened the door for natural selection. Once a self-replicating molecule formed, some variants of these early replicators would have done a better job of copying themselves than others, producing more "offspring." These super-replicators would have become more common — that is, until one of them was accidentally built in a way that allowed it to be a super-super-replicator — and then, that variant would take over. Through this process of continuous natural selection, small changes in replicating molecules eventually accumulated until a stable, efficient replicating system evolved.

3. **Replicating molecules became enclosed within a cell membrane.**
   The evolution of a membrane surrounding the genetic material provided two huge advantages: the products of the genetic material could be kept close by and the internal environment of this proto-cell could be different than the external environment. Cell membranes must have been so advantageous that these encased replicators quickly out-competed "naked" replicators. This breakthrough would have given rise to an organism much like a modern bacterium.
Cell membranes enclose the genetic material.

4. **Some cells began to evolve modern metabolic processes and out-competed those with older forms of metabolism.**
   
   Up until this point, life had probably relied on RNA for most jobs (as described in Step 2 above). But everything changed when some cell or group of cells evolved to use different types of molecules for different functions: DNA (which is more stable than RNA) became the genetic material, proteins (which are often more efficient promoters of chemical reactions than RNA) became responsible for basic metabolic reactions in the cell, and RNA was demoted to the role of messenger, carrying information from the DNA to protein-building centers in the cell. Cells incorporating these innovations would have easily out-competed "old-fashioned" cells with RNA-based metabolisms, hailing the end of the RNA world.

![Diagram of DNA replication and transcription](diagram.png)

1. DNA contains instructions.
2. DNA transcribes RNA.
3. Proteins are made from the instructions.

5. **Multicellularity evolved.**
   
   As early as two billion years ago, some cells stopped going their separate ways after replicating and evolved specialized functions. They gave rise to Earth's first lineage of multicellular organisms, such as the 1.2 billion year old fossilized red algae in the photo below.

![Fossilized red algae](fossil.png)

These fossils of *Bangiomorpha pubescens* are 1.2 billion years old. Toward the lower end of the fossil on the left there are cells differentiated for attaching to a substrate. If you look closely at the upper part of the fossil on the right, you can see longitudinal division that has divided disc-shaped cells into a number of radially arranged wedge-shaped cells, as we would see in a modern bangiophyte red alga.
5.2 How Did Life Begin?

Even the simplest living organisms today—and the similar organisms inferred to have lived more than 3.5 billion years ago—seem remarkably advanced. Metabolic processes involve many intricate molecules and enzymes working together. The complex chemistry of DNA and RNA is deeply intertwined with the proteins and enzymes that help in making them [Section 3.4]. Indeed, every cellular component and process depends on many other components and processes, making it difficult to imagine how one could have developed before another. Nevertheless, life is here, so it must have arisen somehow. In this section, we'll explore what science can tell us about how simple chemical processes on the early Earth might eventually have led to living organisms.

Before we begin, it's worth noting a couple of important caveats. First, we are assuming that life began under the chemical conditions present on the early Earth. If life migrated to Earth, a possibility we will discuss shortly, it's conceivable that it originally arose in a somewhat different chemical environment. Second, we have not said anything about the possibility that life arose through any kind of divine intervention, because such a possibility falls outside the realm of science. Scientifically, we can ask only whether there are natural, chemical processes that could have led to life. As we'll see, a great deal of evidence suggests that there are.

**Organic Chemistry on the Early Earth**

Life today is based on the chemistry of a wide variety of organic molecules. Thus, it's logical to assume that the first life was somehow assembled from organic molecules produced by chemical reactions—without biology—on the early Earth. Scientific experiments support the idea that the early Earth may have been much like a giant laboratory for organic chemistry.

Today, the Earth's oxygen-rich atmosphere prevents complex organic molecules from forming readily outside living cells. Oxygen is such a highly reactive gas that it tends to attack chemical bonds, removing electrons and destroying organic molecules. But as early as the 1920s, some scientists recognized that the oxygen in Earth's atmosphere was a product of life and inferred that the Earth's early atmosphere must have been largely oxygen-free. They further hypothesized that the chemicals in this early atmosphere, fueled by energy from sunlight, would spontaneously create organic molecules. (This idea was proposed independently by Russian biochemist A. I. Oparin and British biologist J. B. S. Haldane.) This hypothesis was put to the test in the 1950s, in a famous experiment credited to Stanley Miller and Harold Urey and now known as the **Miller–Urey experiment** (Figure 5.5).

The original Miller–Urey experiment used small glass flasks to simulate chemical conditions that they thought represented those on the early Earth. One flask was partially filled with water to represent the sea and heated to produce water vapor. Gaseous methane and ammonia were added and mixed with the water vapor to represent the atmosphere. These gases flowed into a second flask, where electric sparks simulated lightning and provided energy for chemical reactions. Below this flask the gas was cooled so it could condense to represent rain and then was cycled back into the water flask. The water soon began to turn a murky brown, and a chemical analysis (performed after letting the experiment run for a week) showed that it contained many amino acids and other organic molecules. Thus, the experiment appeared to support the idea that organic
compounds could form spontaneously under the conditions thought at the time to have been present on the early Earth.

Later discoveries have called into question the relevance of the original Miller–Urey experiment. In particular, we now believe that methane and amino acids were not very abundant in the early atmosphere and that carbon dioxide instead was the most common gas [Section 4.3]. Adding carbon dioxide to the Miller–Urey experiment greatly reduces the amount of organic material produced.

Many scientists have since conducted variations on the Miller–Urey experiment with different mixes of gases thought to be more representative of the Earth’s true early atmosphere. The energy source has also been varied, with some experiments using ultraviolet light (to simulate the effects of sunlight) rather than electrical discharges (which simulate lightning). Although these experiments yield a much smaller total proportion of organic material than did the original Miller–Urey experiment, they still produce a great variety of organic molecules. In fact, various experiments have now produced all the amino acids found in most living organisms, several complex sugars and lipids, and all five of the chemical bases used in DNA and RNA. Nevertheless, given the low overall yield of organic molecules, it’s likely that additional sources of organic molecules were necessary for life to begin.

We know of at least two other potential sources of organic molecules. First, strong evidence suggests that many organic molecules were brought to Earth by impacts. Analysis of meteorites shows that they often contain organic molecules, including complex molecules like amino acids. Similarly, study of comet nuclei in space suggests that they too contain organic molecules. Apparently, organic molecules can form under the conditions present in interplanetary space and can survive the plunge to Earth. Given the large number of impacts that must have occurred during the heavy bombardment, substantial amounts of organic material may have been brought to Earth’s surface by asteroids, comets, and meteors. The heat and pressure generated by the impacts may also have facilitated the production of organic molecules in the Earth’s atmosphere and oceans.

A second additional source of organic molecules may have been chemical reactions near deep-sea vents. As these undersea volcanoes heat the surrounding water, a variety of chemical reactions can occur between the water and the minerals. These chemical reactions would have occurred spontaneously in the conditions thought to have prevailed on the early Earth, and they would have resulted in the production of the same types of organic molecules thought to have been necessary for the origin of life.

It’s likely that all three sources of organic molecules—chemical reactions in the atmosphere, impacts of asteroids and comets, and chemical reactions near deep-sea vents—played a role in shaping the chemistry of the early Earth. More important, given three different ways of obtaining organic molecules, it seems likely that at least parts of the early Earth were like a natural “organic soup” of molecules needed for life. The likelihood of an organic soup near deep-sea vents is particularly encouraging, given the evidence suggesting that life may have originated in such locales. Overall, laboratory studies point strongly to an early Earth containing all the building blocks needed to make life. The next question, then, is how these building blocks might have assembled themselves to make a living cell.

The Transition from Chemistry to Biology
Variations on the Miller–Urey experiment have produced the essential building blocks of life, but, to paraphrase the late Carl Sagan, these building blocks represent only the notes of the music of life, not the music itself. Viewed in terms of simple probability, the likelihood of a set of simple building blocks ramming themselves together to form a complete living organism is at least as small as that of letting monkeys loose in a roomful of musical instruments and hearing Beethoven’s Ninth Symphony. It simply wouldn’t happen, even if the experiment was repeated over and over again for millions of years. There must have been at least a few intermediate steps—each involving a chemical pathway with a relatively high probability of occurring—that eased the transition from chemistry to biology.

The Search for a Self-replicating Molecule
One way to explore the transition is to work backward from organisms living today. Perhaps the single most important feature of any living organism is its ability to reproduce, so we might begin by looking for individual molecules that would be capable of replication. Double-stranded DNA is far too complex—and its replication far too intertwined with RNA and proteins—to be a likely candidate for the original self-replicating molecule. So we are looking for a molecule that is simpler than DNA but still capable of making fairly accurate copies of itself.

The most obvious candidate is RNA. RNA is much simpler than DNA because it has only one strand rather than two and its backbone structure requires fewer steps in its manufacture. But it still possesses hereditary information in the ordering of its bases, and in principle it can serve as a template for making copies of itself. However, for a while, there seemed to be a problem with this idea. In modern organisms, neither DNA nor RNA can replicate
itself. Both require the help of enzymes. These enzymes are proteins, which are made from genetic instructions contained in DNA and carried out with the help of RNA. This fact seemed to present a “chicken and egg” dilemma: RNA cannot replicate without enzymes, and the enzymes cannot be made without RNA.

A way around this dilemma was discovered in the early 1980s by Thomas Cech and his colleagues at the University of Colorado, Boulder. They found that RNA can catalyze biochemical reactions in much the same way as enzymes (work for which Cech shared the Nobel Prize in 1989). We now know that RNA molecules play this type of catalytic role in many cellular functions, and we call such RNA catalysts ribozymes (by analogy to enzymes). A plausible extension of Cech’s work is that RNA or RNA-like molecules might catalyze their own replication. In laboratory experiments to date, RNA-catalyzed reactions have been able to partially (but not completely) replicate another RNA molecule. Encouraged by this result, many biologists envision that early life arose from an “RNA world” in which RNA molecules served both as genes and as chemical catalysts for copying and expressing those genes.

In this scenario, short strands of RNA-like molecules were produced spontaneously on the early Earth (by mechanisms we’ll discuss shortly). Some of the molecules partially or completely catalyzed their own duplication (Figure 5.6), but they varied in their success at this replication. The result was a molecular analog to natural selection: The RNA molecules that replicated faster and more accurately soon came to dominate the population. Copying errors introduced mutations, ensuring the production of many variations of successful molecules. This allowed the molecular evolution to continue, as those RNA molecules best suited to the particular environmental conditions were more likely to continue replicating.

Eventually, the RNA world gave way to the present DNA world. DNA is a more flexible hereditary material and is less prone to copying errors. The similarities between DNA and RNA suggest that RNA molecules could plausibly have evolved from RNA molecules. Moreover, the fact that RNA today is involved in making proteins, which are the workhorses of the modern cell, suggests that RNA existed prior to DNA and retained some of its roles after DNA took over as the hereditary molecule.

Assembling Complex Organic Molecules By itself, the organic soup on the early Earth probably was too dilute to favor the creation of complex molecules like RNA from smaller building blocks. So if there really was an RNA world, how did the RNA molecules come to exist? Laboratory experiments suggest a possible answer. When we place hot sand, clay, or rock in a dilute organic solution, complex molecules self-assemble. Clay may have been especially important to the origin of life.

Clay consists essentially of silicates that have reacted with water, so it should have been common on the early Earth. (In this context, clay refers to a particular physical structure of the minerals, not to a particle size commonly associated with moist dirt.) Minerals in clay contain layers of molecules to which other molecules, including organic molecules, can adhere. Molecules from the dilute organic soup may have stuck to the clay, with the mineral surface structure forcing them into such close proximity that they reacted with one another to form longer chains. Indeed, strands of RNA up to nearly 100 bases in length have been produced in the laboratory in just this way. The repetitive nature of the structure of clay may even have facilitated this production by providing a repeating pattern to act as a template. Other inorganic minerals may have played a similar role. One possibility is the mineral iron pyrite.
(FeS₂), or "fool's gold." The surface of pyrite contains positive charges to which organic molecules can bind. Moreover, the formation of pyrite releases energy that might help fuel the creation of complex organic molecules.

We have no way to be sure that inorganic minerals really did facilitate the production of RNA and other molecules on the early Earth, and unless laboratory experiments someday show that such minerals can take simple organic molecules all the way to something resembling a true living organism, we won’t know if such a scenario is really possible. Nevertheless, we have found plausible ways in which a dilute organic soup may have undergone reactions that built more complex molecules, including self-replicating RNA. The idea of an RNA world no longer seems far-fetched and perhaps was even likely under the conditions present on the young Earth.

**Early Cell-like Structures** The basic unit of living organisms today is the cell, but so far we have talked only about freely floating organic molecules. If these molecules could instead have been confined in some kind of cell-like structure—such as within a simple, membrane-enclosed compartment that we'll call a pre-cell—all the subsequent steps to life would have been much easier.

The advantages of confining organic molecules within a pre-cell are twofold. First, keeping the molecules close together should have increased the rate of reactions among them, making it more likely that cooperative relationships like those in modern cells would evolve. Second, an enclosure would have essentially isolated its contents from the outside world in a way that should have facilitated natural selection among RNA molecules. For example, suppose a particular self-replicating RNA molecule assembled amino acids into a primitive enzyme that sped up replication. If the enzyme floated freely within the organic soup, it might just as easily have helped the replication of other RNA molecules as of the one that made it. But inside a pre-cell, the enzyme would help only the RNA that made it, giving this RNA an advantage over less capable RNA molecules in other pre-cells (Figure 5.7).

Where might such pre-cells have come from? Once again, laboratory experiments suggest that they may have appeared readily on the early Earth. We know of two types of simple membranes that can spontaneously form into pre-cells. First, if we cool a warm-water solution of amino acids, they can form bonds among themselves to make an enclosed, spherical structure (Figure 5.8a). Although they are not alive, these structures exhibit many lifelike properties. For example, they can grow in size by absorbing more short chains of amino acids until they reach an unstable size at which they split to form "daugh-

![Diagram](image)

**FIGURE 5.7** A possible origin of molecular cooperation.

ter" spheres. They can also selectively allow some types of molecules to cross into or out of the enclosure. Some of these spheres even store energy in the form of an electrical voltage across their surfaces, which can be discharged in a way that facilitates reactions inside them. The second type of membrane forms spontaneously when we mix lipids with water (Figure 5.8b). (Recall that lipids are one of the four major types of cellular components [Section 3.2].) Either or both types of membranes might have served as the enclosures of pre-cells, confining RNA and other organic molecules within them.

Was a membrane necessary in order to allow replication of RNA molecules, or were replicating RNA molecules a prerequisite to enclosure in a cell? It's not yet clear which came first. Life might have originated with free-floating RNA molecules that subsequently took advantage of cell membranes to enhance their ability to survive and multiply. Or cell-
like membranes might have originated spontaneously and led to a sufficient concentration of molecules within their interiors to allow replication of RNA-like molecules. Either way, it seems likely that the transition from nonlife to life was gradual. There might never have been a particular moment when we would clearly say that the “first living cell” had appeared on the scene.

**Handedness** We’ve neglected one important issue about the chemistry of life. Recall that many organic molecules come in both left-handed and right-handed versions [Section 3.2]. In general, living organisms preferentially use only one of the two versions of each type of molecule. For example, living organisms use only the left-handed versions of amino acids to make proteins. Nonbiological reactions produce the left- and right-handed versions in roughly equal numbers, so both versions should have been mixed in the organic soup on the early Earth. How, then, did life end up with preferences for a particular version of each molecule?

No one knows the answer to this question, but several hypotheses have been proposed. Perhaps one version of each type of molecule (left-handed or right-handed) has some as-yet-unknown natural advantage over the other version. Or perhaps the molecules eventually became segregated in pre-cells. Some pre-cells might have contained more of one version or the other. It’s conceivable that there might have been both left- and right-handed RNA molecules in different pre-cells, and perhaps even left- and right-handed versions of early organisms. In the latter case, one version may have ultimately died out, leading to the handedness we observe in living organisms today.

**Putting It All Together** We began this section by noting that something as complex as a living cell could not simply have self-assembled from basic building blocks alone. However, we’ve found a plausible set of scenarios that, if correct, would make it much easier for life to form. In essence, we’ve supposed that life on the Earth originated in a series of steps, each of which seems reasonably likely. Thus, the complex structures of life were built up gradually rather than originating all at once. Let’s review the sequence we have envisioned (Figure 5.9):

1. Through some combination of atmospheric chemistry, chemistry near deep-sea vents, and impacts of asteroids and comets, the early Earth developed at least localized areas in which amino acids, building blocks of nucleic acids, and other organic molecules were dissolved in a dilute “organic soup.”

2. More complex molecules, including short strands of RNA, grew from the building blocks in the organic soup, perhaps with the aid of reactions using clay or other mineral surfaces as templates for their assembly. Some of the RNA molecules were capable of self-replication.

3. Membranes that formed spontaneously in the organic soup enclosed some of these complex molecules, making “pre-cells” that facilitated the development of cooperative molecular interactions.

4. Natural selection among the RNA molecules in pre-cells gradually led to an increase in complex-
ity, until eventually some of these structures became true living organisms.

5. Natural selection then rapidly improved and diversified life. DNA became the favored hereditary molecule, and life has continued to evolve ever since.

We may never know whether life actually originated in this way, in some similar way, or in some completely different way. Nevertheless, this scenario seems quite reasonable and perhaps even "easy" given geological time scales. It seems especially reasonable given that a number of different components of the scenario have been demonstrated in laboratory experiments. Even if life did not originate in this way, it seems that it could have—which suggests that the actual path to life must have been equally easy, or it would have followed the path we've described. In summary, we have reason to believe that the origin of life was a likely consequence of conditions on the early Earth, in which case it might be equally likely that life arose on many other worlds.

**THINK ABOUT IT . . .** We've noted that the probability of life's arising by randomly mixing simple organic building blocks is so small as to seem impossible. Yet, in the scenario we've described, the likelihood of getting life seems quite good. In your own words, describe why these two probabilities are so different.

**Could Life Have Migrated to Earth?**

We have no reason at present to think that life came to Earth from somewhere else, because it seems quite plausible that life could have arisen here on its own. Nevertheless, it's still possible that life migrated to Earth (an idea sometimes called "panspermia").

The idea that life could travel through space to land on Earth once seemed outlandish. After all, it's hard to imagine a more forbidding environment than that of space, where there's no air, no water, and constant bombardment by dangerous radiation from the Sun and stars. However, the presence of organic molecules in meteorites and comets tells us that the building blocks of life can survive in the space environment, and some microbes seem capable of surviving at least moderate periods of time in space (Section 3.5). It therefore seems possible that life could migrate from one planet to another, perhaps within the interior of a rock blasted from a planetary surface by an impact.

Indeed, the key question probably is not whether life could migrate through space but whether we have any reason to suppose it originated elsewhere rather than right here on Earth. Many scientists have debated this question, with the debate taking many different twists. Today, most ideas about migrating life fall into one of two broad categories.

The first broad idea suggests that life does not form as easily as we have imagined, at least under the conditions present on the early Earth, and that the relatively short time between the last sterilizing impact and the earliest appearance of life was not long enough for life to have originated here. In this view, the only explanation for life on Earth (other than invoking the supernatural) would be migration from elsewhere. Although this idea in some sense only moves the problem of life's origin to another place, it at least allows for the possibility that more time was available for life to develop (or conditions were more conducive to rapid development) in this other place than on Earth. The primary drawback to this idea is that other worlds in our solar system probably had similar constraints on the early origin of life—such as sterilizing impacts during the heavy bombardment. The only way to get significantly more time for an origin of life is to suppose that life migrated from another star system, but interstellar migration by microbes seems highly unlikely. Such a journey would require millions or billions of years; living organisms would almost surely be killed by exposure to cosmic rays during this time. Moreover, calculations suggest that the probability of a rock from another star system hitting Earth is extremely low, which also explains why we have never found a meteorite from beyond our own solar system.

The second broad idea, in contrast, suggests that life forms so easily that we should expect to find life originating on any planet with suitable conditions. Earth might not have been the first planet in our solar system with conditions suitable for life. If life originated on a different planet first—say, on Mars—it might have migrated to Earth and taken hold on our planet as soon as conditions allowed. In essence, this idea suggests that life could have originated on Earth but never got the chance because life from another planet got here first.

Like most of what we've discussed concerning the possible origin of life, we simply do not have enough data to decide definitively whether life began on Earth or followed either migration scenario. But the mere possibility of life's migrating among worlds is interesting and will surely be investigated further as scientists continue to study the question of life in the universe.

**5.3 Early Evolution and the Rise of Oxygen**

Regardless of how it originated, life on Earth has flourished for some 3.5-4.0 billion years. For most of that time, life was very simple; complex, multicelled organisms arose only recently on the geological time scale. In this section, we'll briefly trace how the