CHAPTER 2

The Miller-Urey Experiment

Accompanied by music from Stravinsky's *Rite of Spring*, the primordial Earth seethes with volcanic activity. Red-hot lava flows over the land and tumbles into the sea, generating clouds of steam while lightning flashes in the sky above. Slowly, the camera pans down until it reaches the calm depths of the ocean, where mysterious specks glow in the dark. Suddenly, a single-celled animal darts across the screen. Life is born.

The scene is from Walt Disney's 1940 film classic, *Fantasia,* and the narrator calls it "a coldly accurate reproduction of what science thinks went on during the first few billion years of this planet's existence." The scenario was the brain-child of Russian scientist A. I. Oparin and British scientist J. B. S. Haldane, who in the 1920s had suggested that lightning in the primitive atmosphere could have produced the chemical building blocks of life. Although Darwin did not pretend to understand the origin of life, he speculated that it might have started in "some warm little pond." Similarly, Oparin and Haldane hypothesized that chemicals produced in the atmosphere dissolved in the primordial seas to form a "hot dilute soup," from which the first living cells emerged.

From: *Icons of Evolution – Science or Myth? Why much of what we teach about evolution is wrong*, by Jonathan Wells

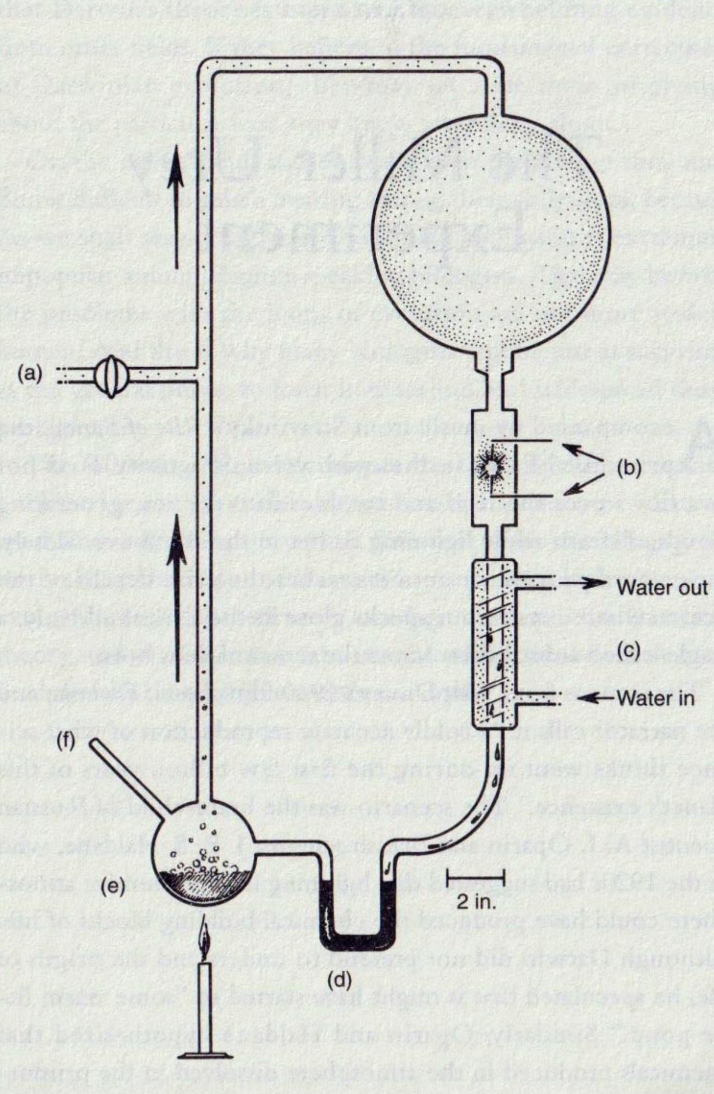

FIGURE 2-1 The 1953 Miller-Urey Experiment.

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(a) Vacuum line; (b) high-voltage spark electrodes; (c) condenser with circulating cold water; (d) trap to prevent backflow; (e) flask for boiling water and collecting reaction products; (f) sealed tube, broken later to remove reaction products for analysis. In later experiments, the electrodes were moved up into the large flask at the upper right, and a stopcock for withdrawing reaction products was added to the trap at the bottom. Most textbook drawings show these later modifications.

The Oparin-Haldane hypothesis captured the imagination of many scientists, and thus became "what science thinks" about the first steps in the origin of life. But it remained an untested hypothesis until the early 1950s, when an American graduate student, Stanley Miller, and his Ph.D. advisor, Harold Urey, produced some of the chemical building blocks of life by sending an electric spark through a mixture of gases they thought simulated the Earth's primitive atmosphere. (Figure 2-1) The 1953 Miller-Urey experiment generated enormous excitement in the scientific community, and soon found its way into almost every high school and college biology textbook as evidence that scientists had demonstrated the first step in the origin of life.

The Miller-Urey experiment is still featured prominently in textbooks, magazines, and television documentaries as an icon of evolution. Yet for more than a decade most geochemists have been convinced that the experiment failed to simulate conditions on the early Earth, and thus has little or nothing to do with the origin of life. Here's why.

The Oparin-Haldane scenario

The first step in the Oparin-Haldane scenario—the production of life's chemical building blocks by lightning—depends crucially on the composition of the atmosphere. The Earth's present atmosphere is about 21 percent oxygen gas. We tend to think of an oxygen-rich atmosphere as essential to life, because we would die without it. Yet, paradoxically, life's building blocks could not have formed in such an atmosphere.

We need oxygen because our cells produce energy through aerobic respiration (though some bacteria are "anaerobic," and thrive in the absence of oxygen). In effect, aerobic organisms use oxygen to get energy from organic molecules in much the same way that automobile engines use oxygen to get energy from gasoline. But our bodies must also synthesize organic molecules, otherwise we could not grow, heal, or reproduce. Respiration, which breaks down organic molecules, is the opposite of synthesis, which builds them up. Chemists call the process of respiration "oxidizing," while they call the process of synthesis "reducing."

Not surprisingly, the same oxygen that is essential to aerobic respiration is often fatal to organic synthesis. An electric spark in a closed container of swamp gas (methane) might produce some interesting organic molecules, but if even a little oxygen is present the spark will cause an explosion. Just as a closed container excludes oxygen and prevents swamp gas from exploding, so compartments in living cells exclude oxygen from the processes of organic synthesis. Free oxygen in the wrong places can be harmful to health, which is why some nutritionists tell people to consume more "anti-oxidant" vitamins.

Since free oxygen can destroy many organic molecules, chemists often must remove oxygen and use closed containers

when they synthesize and store organic chemicals in the laboratory. But before the origin of life, when there were neither chemists nor laboratories, the chemical building blocks of life could have formed only in a natural environment lacking oxygen. According to Oparin and Haldane, that environment was the Earth's primitive atmosphere.

The Earth's present atmosphere is strongly oxidizing. Oparin and Haldane postulated its exact opposite: a strongly reducing atmosphere rich in hydrogen. Specifically, they postulated a mixture of methane (hydrogen combined with carbon), ammonia (hydrogen combined with nitrogen), water vapor (hydrogen combined with oxygen) and hydrogen gas. Oparin and Haldane predicted that lightning in such an atmosphere could spontaneously produce the organic molecules needed by living cells.

The Miller-Urey experiment

At the time, it seemed reasonable to postulate a strongly reducing primitive atmosphere. Scientists believed that the Earth originally formed from a condensing cloud of interstellar dust and gas, so it was reasonable to suppose that the original atmosphere resembled interstellar gases, which consist predominantly of hydrogen. In 1952, Nobel Prize-winning chemist Harold Urey concluded that the early atmosphere consisted primarily of hydrogen, methane, ammonia and water vapor—just as Oparin and Haldane had postulated.

Urey's graduate student at The University of Chicago, Stanley Miller, set out to test the Oparin-Haldane hypothesis experimentally. Miller assembled a closed glass apparatus in Urey's laboratory, pumped out the air, and replaced it with methane, ammonia, hydrogen and water. (If he hadn't removed the air, his next step might have been his last.) He then heated the water and circulated the gases past a high-voltage electric spark to simulate lightning. (Figure 2-1)

"By the end of the week," Miller reported, the water "was deep red and turbid." He removed some of it for chemical analysis and identified several organic compounds. These included glycine and alanine, the two simplest amino acids found in proteins. Most of the reaction products, however, were simple organic compounds that do not occur in living organisms.

Miller published his initial results in 1953. By repeating the experiment, he and others were able to obtain small yields of most biologically significant amino acids, as well as some additional organic compounds found in living cells. The Miller-Urey experiment thus seemed to confirm the Oparin-Haldane hypothesis about the first step in the origin of life. By the 1960s, however, geochemists were beginning to doubt that conditions on the early Earth were the ones Oparin and Haldane had postulated.

Did the primitive atmosphere really lack oxygen?

Urey assumed that the Earth's original atmosphere had the same composition as interstellar gas clouds. In 1952, however (the same year Urey published this view), University of Chicago geochemist Harrison Brown noted that the abundance of the rare gases neon, argon, krypton, and xenon in the Earth's atmosphere was at least a million times lower than the cosmic average, and concluded that the Earth must have lost its original atmosphere (if it ever had one) very soon after its formation.

In the 1960s Princeton University geochemist Heinrich Holland and Carnegie Institution geophysicist Philip Abelson agreed with Brown. Holland and Abelson independently concluded that

the Earth's primitive atmosphere was *not* derived from interstellar gas clouds, but from gases released by the Earth's own volcanoes. They saw no reason to believe that ancient volcanoes were different from modern ones, which release primarily water vapor, carbon dioxide, nitrogen, and trace amounts of hydrogen. Since hydrogen is so light, Earth's gravity would have been unable to hold it, and (like the rare gases) it would quickly have escaped into space.

But if the principal ingredient of the primitive atmosphere was water vapor, the atmosphere must also have contained some oxygen. Atmospheric scientists know that ultraviolet rays from sunlight cause dissociation of water vapor in the upper atmosphere. This process, called "photodissociation," splits water molecules into hydrogen and oxygen. The hydrogen escapes into space, leaving the oxygen behind in the atmosphere. (Figure 2-2)

Scientists believe that most of the oxygen in the present atmosphere was produced later by photosynthesis, the process by which green plants convert carbon dioxide and water into organic matter and oxygen.

Nevertheless, photodissociation would have generated small amounts of oxygen even before the advent of photosynthesis. The question is, how much?

In 1965 Texas scientists L. V. Berkner and L. C. Marshall argued that the oxygen produced by photodissociation could not have exceeded about one thousandth of its present atmospheric level, and was probably much lower. California Institute of Technology geophysicist R. T. Brinkmann disagreed, claiming that "appreciable oxygen concentrations might have evolved in the Earth's atmosphere"—as much as one quarter of the present level—before the advent of photosynthesis. As the controversy over theoretical implications widened, various scientists took one side or the other: Australian geologist J. H. Carver concurred with Brinkmann, while Pennsylvania State University geologist James Kasting agreed with Berkner and Marshall. The issue was never resolved.

Evidence from ancient rocks has been inconclusive. Some ancient sedimentary rocks contain uraninite, an oxygen-poor uranium compound that suggests to some geologists that those sediments had been laid down in an oxygen-poor atmosphere. But other geologists point out that uraninite also occurs in later rocks that were deposited in our modern oxygen-rich atmosphere. Sediments rich in the highly oxidized red form of iron have also been used to infer primitive oxygen levels. Geologist James C. G. Walker argued that the appearance of these "red-beds" about two billion years ago "marks the beginning of the aerobic atmosphere." But red-beds also occur in rocks older than two billion years, and Canadian geologists Erich Dimroth and Michael Kimberly wrote in 1979 that they saw "no evidence" in the sedimentary distribution of iron "that an oxygen-free atmosphere has existed at any time during the span of geological history recorded in well preserved sedimentary rocks."

Biochemical evidence has been used to infer primitive oxygen levels, as well. In 1975 British biologists J. Lumsden and D. O. Hall reported that an enzyme (superoxide dismutase) used by living cells to protect themselves from the damaging effects of oxygen is present even in organisms whose ancestors are thought to have existed before the advent of photosynthesis. Lumsden and Hall concluded that the enzyme must have evolved to provide protection against primitive oxygen produced by photodissociation.

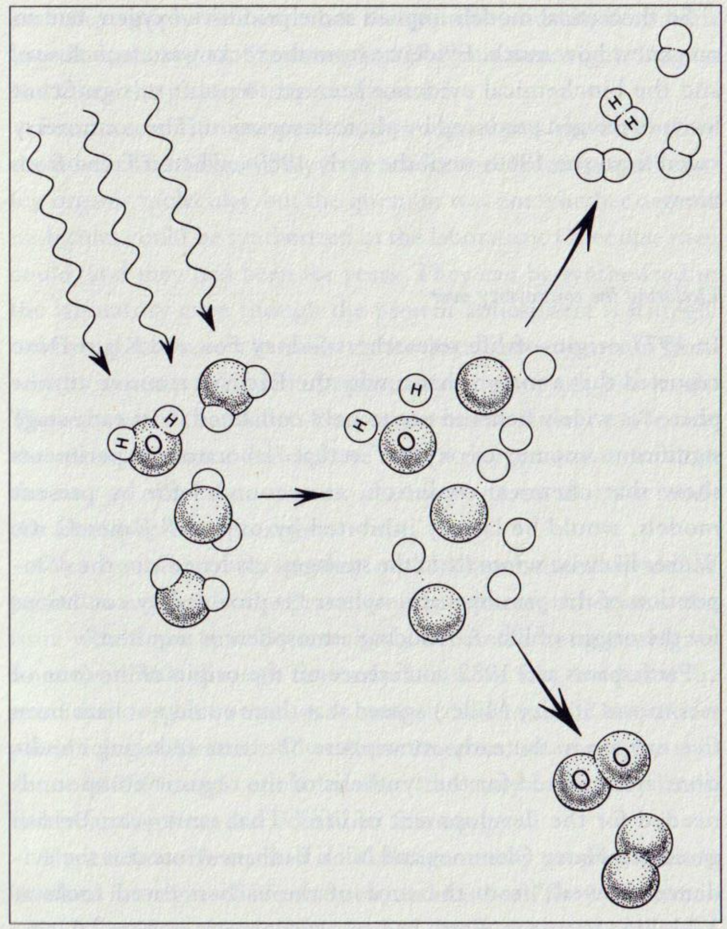

FIGURE 2-2 Photodissociation.

Water molecules (oxygen plus hydrogen) are split by ultraviolet rays from sunlight in the upper atmosphere. The hydrogen (H) is too light to be held by Earth's gravity and escapes into outer space, while the heavier oxygen (O) remains in the atmosphere.

So theoretical models implied some primitive oxygen, but no one knew how much. Evidence from the rocks was inconclusive, and the biochemical evidence seemed to point to significant levels of oxygen produced by photodissociation. The controversy raged from the 1960s until the early 1980s, when it faded from view.

Declaring the controversy over

In 1977 origin-of-life researchers Sidney Fox and Klaus Dose reported that a major reason why the Earth's primitive atmosphere "is widely believed not to have contained in its early stage significant amounts of oxygen" is that "laboratory experiments show that chemical evolution, as accounted for by present models, would be largely inhibited by oxygen." James C. G. Walker likewise wrote that "the strongest evidence" for the composition of the primitive atmosphere "is provided by conditions for the origin of life. A reducing atmosphere is required."

Participants at a 1982 conference on the origin of life (one of whom was Stanley Miller) agreed that there could not have been free oxygen in the early atmosphere "because reducing conditions are required for the synthesis of the organic compounds needed for the development of life." That same year, British geologists Harry Clemmey and Nick Badham wrote that the evidence showed "from the time of the earliest dated rocks at 3.7 billion years ago, Earth had an oxygenic atmosphere." Clemmey and Badham declared it a mere "dogma" to claim that the Earth's early atmosphere lacked oxygen.

But geological and biochemical evidence no longer mattered, because certain influential scientists decided that the Miller-Urey experiment had demonstrated the first step in the origin of life,

and they simply declared that the primitive atmosphere must have lacked oxygen. Clemmey and Badham were right. Dogma had taken the place of empirical science.

From a scientific perspective, this dogma puts the cart before the horse. The Miller-Urey experiment succeeded in synthesizing organic molecules, but the question was not whether organic molecules could be synthesized in the laboratory. Of course they could, and they had been for years. They can be synthesized in the laboratory even though the present atmosphere is strongly oxidizing, because chemists create local environments from which oxygen is excluded or maintained at extremely low levels. The success of the Miller-Urey experiment doesn't prove that the entire primitive atmosphere lacked oxygen any more than the success of modern organic chemistry proves that the modern atmosphere lacks oxygen.

Clearly, some of the geological and biochemical evidence points to oxygen in the primitive atmosphere; otherwise, the issue would not have been so hotly debated among geologists from the 1960s through the early 1980s. In fact, evidence for primitive oxygen continues to mount: Smithsonian Institution paleobiologist Kenneth Towe (now emeritus) reviewed the evidence in 1996, and concluded that "the early Earth very likely had an atmosphere that contained free oxygen."

The evidence Towe cited is usually ignored by people currently involved in origin-of-life research, and has been for years. Ironically, however, not even this arbitrary dismissal of evidence saved the Miller-Urey experiment. Although geochemists were sharply divided on the oxygen issue, they soon reached a near-consensus that the primitive atmosphere was nothing like the one Miller used.

The Miller-Urey experiment fails anyway

Holland and Abelson concluded in the 1960s that the Earth's primitive atmosphere was derived from volcanic outgassing, and consisted primarily of water vapor, carbon dioxide, nitrogen, and trace amounts of hydrogen. With most of the hydrogen being lost to space, there would have been nothing to reduce the carbon dioxide and nitrogen, so methane and ammonia could not have been major constituents of the early atmosphere. (Figure 2-3)

Abelson also noted that ammonia absorbs ultraviolet radiation from sunlight, and would have been rapidly destroyed by it. Furthermore, if large amounts of methane had been present in the primitive atmosphere, the earliest rocks would have contained a high proportion of organic molecules, and this is not the case. Abelson concluded: "What is the evidence for a primitive methane-ammonia atmosphere on Earth? The answer is that there is *no* evidence for it, but much against it." (emphasis in original) In other words, the Oparin-Haldane scenario was wrong, and the early atmosphere was nothing like the strongly reducing mixture used in Miller's experiment.

Other scientists agreed. In 1975 Belgian biochemist Marcel Florkin announced that "the concept of a reducing primitive atmosphere has been abandoned," and the Miller-Urey experiment is "not now considered geologically adequate." Sidney Fox and Klaus Dose—though they argued that the primitive atmosphere lacked oxygen—conceded in 1977 that a reducing atmosphere did "not seem to be geologically realistic because evidence indicates that... most of the free hydrogen probably had disappeared into outer space and what was left of methane and ammonia was oxidized."

According to Fox and Dose, not only did the Miller-Urey experiment start with the wrong gas mixture, but also it did "not satisfactorily represent early geological reality because no provisions [were] made to remove hydrogen from the system." During a Miller-Urey experiment hydrogen gas accumulates, becoming up to 76 percent of the mixture, but on the early Earth it would have escaped into space. Fox and Dose concluded: "The inference that Miller's synthesis does not have a geological relevance has become increasingly widespread."

Since 1977 this view has become a near-consensus among geochemists. As Jon Cohen wrote in *Science* in 1995, many origin-of-life researchers now dismiss the 1953 experiment because "the early atmosphere looked nothing like the Miller-Urey simulation."

So what? Maybe a water vapor–carbon dioxide–nitrogen atmosphere would still support a Miller–Urey-type synthesis (as long as oxygen is excluded). But Fox and Dose reported in 1977 that no amino acids are produced by sparking such a mixture, and Heinrich Holland noted in 1984 that the "yields and the variety of organic compounds produced in these experiments decrease considerably" as methane and ammonia are removed from the starting mixtures. According to Holland, mixtures of carbon dioxide, nitrogen, and water yielded no amino acids at all.

In 1983 Miller reported that he and a colleague were able to produce a small amount of the simplest amino acid, glycine, by sparking an atmosphere containing carbon monoxide and carbon dioxide instead of methane, as long as free hydrogen was present. But he conceded that glycine was about the best they could do in the absence of methane. As John Horgan wrote in *Scientific American* in 1991, an atmosphere of carbon dioxide, nitrogen,

OXIDIZING (present Earth)	**NEUTRAL** (volcanic outgassing)	**REDUCING** (Oparin-Haldane)
nitrogen	**water vapor** (hydrogen + oxygen)	**methane** (carbon + hydrogen)
oxygen	**carbon dioxide** (carbon + oxygen)	**ammonia** (nitrogen + hydrogen)
carbon dioxide (carbon + oxygen)	**nitrogen**	**hydrogen**
water vapor (hydrogen + oxygen)	**hydrogen** (trace; lost to space)	**water vapor** (oxygen + hydrogen)

FIGURE 2-3 A comparison of oxidizing, neutral, and reducing atmospheres

Constituents are listed from top to bottom in order of their prevalance.

and water vapor "would not have been conducive to the synthesis of amino acids."

The conclusion is clear: if the Miller-Urey experiment is repeated using a realistic simulation of the Earth's primitive atmosphere, it doesn't work. Therefore, origin-of-life researchers have had to look elsewhere.

An RNA world?

Since the Miller-Urey experiment fails to explain how proteins could have formed on the early Earth, origin-of-life researchers have considered the possibility that proteins were not the first molecular building-blocks of life. DNA is not a good candidate, because it needs a whole suite of complex proteins to make copies of itself. Therefore DNA could not have originated

before proteins, and could not have been the first step in the origin of life.

Another candidate is RNA, a close chemical relative of DNA that is used by all living cells in the process of making proteins. In the 1980s molecular biologists Thomas Cech and Sidney Altman showed that RNA can sometimes behave like an enzyme—that is, like a protein. Another molecular biologist, Walter Gilbert, suggested that RNA might be able to synthesize itself in the absence of proteins, and thus might have originated on the early Earth before either proteins or DNA. This "RNA world" might then have been the molecular cradle from which living cells emerged.

But no one has demonstrated how RNA could have formed before living cells were around to make it. According to Scripps Research Institute biochemist Gerald Joyce, RNA is not a plausible candidate for the first building block of life "because it is unlikely to have been produced in significant quantities on the primitive Earth." Even if RNA could have been produced, it would not have survived long under the conditions thought to have existed on the early Earth.

Joyce concludes: "The most reasonable interpretation is that life did not start with RNA." Although he still thinks that an RNA world preceded the DNA world, he believes that some kind of living cells must have preceded RNA. "You have to build straw man upon straw man," Joyce said in 1998, "to get to the point where RNA is a viable first biomolecule."

In other words, the RNA world—like the protein-first scenario in the Miller-Urey experiment—is a dead end. Origin-of-life researchers have been unable to show how the molecular building blocks of life formed on the early Earth. But even if they had discovered the origin of the building blocks, the origin of life would remain a mystery. A biochemist can mix all the chemical building blocks of life in a test tube and still not produce a living cell.

The origin of life problem is so difficult that German researcher Klaus Dose wrote in 1988 that current theory is "a scheme of ignorance. Without fundamentally new insights in evolutionary processes... this ignorance is likely to persist." And persist it has. In 1998, comparing the scientific search for the origin of life to a detective story, Salk Institute scientist Leslie Orgel acknowledged that "we are very far from knowing whodunit." And *New York Times* science writer Nicholas Wade reported in June 2000: "Everything about the origin of life on Earth is a mystery, and it seems the more that is known, the more acute the puzzles get."

So we remain profoundly ignorant of how life originated. Yet the Miller-Urey experiment continues to be used as an icon of evolution, because nothing better has turned up. Instead of being told the truth, we are given the misleading impression that scientists have empirically demonstrated the first step in the origin of life.

The Miller-Urey experiment as an icon of evolution

The March 1998 issue of *National Geographic* carries a photo of Miller standing next to his experimental apparatus. The caption reads: "Approximating conditions on the early Earth in a 1952 experiment, Stanley Miller—now at the University of California at San Diego—produced amino acids. 'Once you get the equipment together it's very simple,' he says."

Several pages later, the *National Geographic* article explains: "Many scientists now suspect that the early atmosphere was different from what Miller first supposed." But a picture is worth a thousand words—especially when its caption is misleading and the truth is buried deep in the article. Even a careful reader is left with the impression that the Miller-Urey experiment showed how easy it was for life to originate on the early Earth.

Many biology textbooks use the same misleading approach. The 2000 edition of Kenneth Miller and Joseph Levine's *Biology,* a popular high school textbook, includes a drawing of the Miller-Urey apparatus with the caption: "By re-creating the early atmosphere (ammonia, water, hydrogen and methane) and passing an electric spark (lightning) through the mixture, Miller and Urey proved that organic matter such as amino acids could have formed spontaneously." Like the *National Geographic* article, the Miller-Levine textbook buries a disclaimer in the text: "Miller's original guesses about the Earth's early atmosphere were probably incorrect," but even this is softened by adding that experiments using other mixtures "also have produced organic compounds." In any case, the textbook is quite adamant that the ancient atmosphere "did not contain oxygen gas."

The 1998 college textbook, *Life: The Science of Biology* by William Purves, Gordon Orians, Craig Heller, and David Sadava, tells students that Stanley Miller produced "the building blocks of life" using "a reducing atmosphere such as existed on early Earth," and that "no free oxygen was present in this early atmosphere." This textbook gives students no hint that most scientists now think the Miller-Urey experiment failed to simulate actual conditions on the early Earth.

Even advanced college textbooks misrepresent the truth. The 1998 edition of Douglas Futuyma's *Evolutionary Biology* includes a drawing of "the apparatus Miller used to synthesize organic molecules under simulated early Earth conditions." The only thing Futuyma's book has to say about the controversy over primitive oxygen is that "at the time of the earliest life, the atmosphere virtually lacked oxygen." And the latest edition of *Molecular Biology of the Cell*, a graduate level textbook by National Academy of Sciences President Bruce Alberts and his colleagues, features the Miller-Urey apparatus and calls it "a typical experiment simulating conditions on the primitive Earth." The accompanying text asserts that organic molecules "are likely to have been produced under such conditions. The best evidence for this comes from laboratory experiments."

A 1999 booklet published by the National Academy of Sciences perpetuates the misrepresentation: "Experiments conducted under conditions intended to resemble those present on primitive Earth have resulted in the production of some of the chemical components of proteins." This booklet includes a preface by Bruce Alberts, who (as we saw in the Introduction) assures us that "science and lies cannot coexist."

This is even more troubling than the misuse of the Miller-Urey experiment by *National Geographic* and biology textbooks. The National Academy of Sciences is the nation's premier science organization, commissioned by Congress in 1863 to advise the government on scientific matters. Its members include many of the best scientists in America. Do they really approve of misleading the public about the evidence for evolution? Or is this being done without the members' knowledge? What are the American people supposed to think?

As we shall see in the following chapters, booklets published recently by the National Academy contain other false and misleading statements about evolution, too. Clearly, we are not dealing here with an isolated textbook error. The implications for American science are potentially far-reaching.

In 1986 chemist Robert Shapiro wrote a book criticizing several aspects of research on the origin of life. He was especially critical of the argument that the Miller-Urey experiment proved that the Earth's primitive atmosphere was strongly reducing. "We have reached a situation," he wrote, "where a theory has been accepted as fact by some, and possible contrary evidence is shunted aside." He concluded that this is "mythology rather than science."

Are we teaching our biology students mythology rather than science?