THE MILLER-UREY EXPERIMENT

THE EXPERIMENT ITSELF

The understanding of the origin of life was largely speculative until the 1920s, when Oparin and Haldane, working independently, proposed a theoretical model for "chemical evolution." The Oparin–Haldane model suggested that under the strongly reducing conditions theorized to have been present in the atmosphere of the early earth (between 4.0 and 3.5 billion years ago), inorganic molecules would spontaneously form organic molecules (simple sugars and amino acids). In 1953, Stanley Miller, along with his graduate advisor Harold Urey, tested this hypothesis by constructing an apparatus that simulated the Oparin-Haldane "early earth." When a gas mixture based on predictions of the early atmosphere was heated and given an electrical charge, organic compounds were formed (Miller, 1953; Miller and Urey, 1959). Thus, the Miller-Urey experiment demonstrated how some biological molecules, such as simple amino acids, could have arisen abiotically, that is through non-biological processes, under conditions thought to be similar to those of the early earth. This experiment provided the structure for later research into the origin of life. Despite many revisions and additions, the Oparin–Haldane scenario remains part of the model in use today. The Miller–Urey experiment is simply a part of the experimental program produced by this paradigm.

WELLS BOILS OFF

Wells says that the Miller–Urey experiment should not be taught because the experiment used an atmospheric composition that is now known to be incorrect. Wells contends that textbooks don't discuss how the early atmosphere was probably different from the atmosphere hypothesized in the original experiment. Wells then claims that the actual atmosphere of the early earth makes the Miller–Urey type of chemical synthesis impossible, and asserts that the experiment does not work when an updated atmosphere is used. Therefore, textbooks should either discuss the experiment as an historically interesting yet flawed exercise, or not discuss it at all. Wells concludes by saying that textbooks should replace their discussions of the Miller–Urey experiment with an "extensive discussion" of all the problems facing research into the origin of life.

These allegations might seem serious; however, Wells's knowledge of prebiotic chemistry is seriously flawed. First, Wells's claim that researchers are ignoring the new atmospheric data, and that experiments like the Miller–Urey experiment fail when the atmospheric composition reflects current theories, is simply false. The current literature shows that scientists working on the origin and early evolution of life are well aware of the current theories of the earth's early atmosphere and have found that the revisions have little effect on the results of various experiments in biochemical synthesis. Despite Wells's claims to the contrary, new experiments since the Miller–Urey ones have achieved similar results using various corrected atmospheric compositions (Figure 1; Rode, 1999; Hanic et al., 2000). Further, although some authors have argued that electrical energy might not have efficiently produced organic molecules in the earth's early atmosphere, other energy sources such as cosmic radiation (e.g., Kobayashi et al., 1998), high temperature impact events (e.g., Miyakawa et al., 2000), and even the action of waves on a beach (Commeyras et al., 2002) would have been quite effective.

Even if Wells had been correct about the

Researcher(s)	Year	Reactants	Energy source	Results	Probability
Miller	1953	CH_4, NH_3, H_2O, H_2	Electric discharge	Simple amino acids, organic compounds	unlikely
Abelson	1956	CO, CO_2, N_2, NH_3, H_2, H2O	Electric discharge	Simple amino acids, HCN	unlikely
Groth and Weyssenhoff	1957	CH_4, NH_3, H_2O	Ultraviolet light (1470–1294 ?)	Simple amino acids (low yields)	under special conditions
Bahadur, et al.	1958	Formaldehyde, molybdenum oxide	Sunlight (photosynthesis)	Simple amino acids	possible
Pavolvskaya and Pasynskii	1959	Formaldehyde, nitrates	High pressure Hg lamp (photolysis)	Simple amino acids	possible
Palm and Calvin	1962	CH_4, NH_3, H_2O	Electron irradiation	Glycine, alanine, aspartic acid	under special conditions
Harada and Fox	1964	CH_4, NH_3, H_2O	Thermal energy (900–1200º C)	14 of the “essential” amino acids of proteins	under special conditions
Oró	1968	CH_4, NH_3, H_2O	Plasma jet	Simple amino acids	unlikely
Bar-Nun et al.	1970	CH_4, NH_3, H_2O	Shock wave	Simple amino acids	under special conditions
Sagan and Khare	1971	CH_4, C_2H_6, NH_3, H_2O, H2S	Ultraviolet light (>2000 ?)	Simple amino acids (low yields)	under special conditions
Yoshino et al.	1971	H_2, CO, NH_3, montmorillonite	Temperature of 700°C	Glycine, alanine, glutamic acid, serine, aspartic acid, leucine, lysine, arginine	unlikely
Lawless and Boynton	1973	CH_4, NH_3, H_2O	Thermal energy	Glycine, alanine, aspartic acid, ?-alanine, N-methyl-?-alanine, ?-amino-n-butyric acid.	under special conditions
Yanagawa et al.	1980	Various sugars, hydroxylamine, inorganic salts,	Temperature of 105°C	Glycine, alanine, serine, aspartic acid, glutamic acid	under special conditions
Kobayashi et al.	1992	CO, N_2, H_2O	Proton irradiation	Glycine, alanine, aspartic acid, ?-alanine, glutamic acid, threonine, ?-aminobutyric acid, serine	possible
Hanic, et al.	1998	CO_2, N_2, H_2O	Electric discharge	Several amino acids	possible

Figure 1. *A table of some amino acid synthesis experiments since Miller–Urey. The “probability” column reflects the likelihood of the environmental conditions used in the experiment. Modified from Rode, 1999.*

Miller–Urey experiment, he does not explain that our theories about the origin of organic “building blocks” do not depend on that experiment alone (Orgel, 1998a). There are other sources for organic “building blocks,” such as meteorites, comets, and hydrothermal vents. All of these alternate sources for organic materials and their synthesis are extensively discussed in the literature about the origin of life, a literature that Wells does not acknowledge. In fact, what is most striking about Wells’s extensive reference list is the literature that he has left out. Wells does not mention extraterrestrial sources of organic molecules, which have been widely discussed in the literature since 1961 (see Oró, 1961; Whittet, 1997; Irvine, 1998). Wells apparently missed the vast body of literature on organic compounds in comets (e.g. Oró, 1961; Anders, 1989; Irvine, 1998), carbonaceous meteorites (e.g., Kaplan et al., 1963; Hayes, 1967; Chang, 1994; Maurette, 1998; Cooper et al., 2001), and conditions conducive to the formation of organic compounds that exist in interstellar dust clouds (Whittet, 1997).

Wells also fails to cite the scientific literature on other terrestrial conditions under which organic compounds could have formed. These non-atmospheric sources include the synthesis of organic compounds in a reducing ocean (e.g., Chang, 1994), at hydrothermal vents (e.g., Andersson, 1999; Ogata et al., 2000), and in volcanic aquifers (Washington, 2000). A cursory review of the literature finds more than 40 papers on terrestrial prebiotic chemical synthesis published since 1997 in the journal *Origins of life and the evolution of the biosphere* alone. Contrary to Wells's presentation, there appears to be no shortage of potential sources for organic "building blocks" on the early earth.

Instead of discussing this literature, Wells raises a false "controversy" about the low amount of free oxygen in the early atmosphere. Claiming that this precludes the spontaneous origin of life, he concludes that "[d]ogma had taken the place of empirical science" (Wells, 2000:18). In truth, nearly *all* researchers who work on the early atmosphere hold that oxygen was essentially absent during the period in which life originated (Copley, 2001) and therefore oxygen could not have played a role in preventing chemical synthesis. This conclusion is based on many sources of *data*, not "dogma." Sources of data include fluvial uraninite sand deposits (Rasmussen and Buick, 1999) and banded iron formations (Nunn, 1998; Copley, 2001), which could not have been deposited under oxidizing conditions. Wells also neglects the data from paleosols (ancient soils) which, because they form at the atmosphere–ground interface, are an excellent source to determine atmospheric composition (Holland, 1994). Reduced paleosols suggest that oxygen levels were very low before 2.1 billion years ago (Rye and Holland, 1998). There are also data from mantle chemistry that suggest that oxygen was essentially absent from the earliest atmosphere (Kump et al., 2001). Wells misrepresents the debate as over whether oxygen levels were 5/100 of 1%, which Wells calls "low," or 45/100 of 1%, which Wells calls "significant." But the controversy is really over why it took so long for oxygen levels to start to rise. Current data show that oxygen levels did not start to rise significantly until nearly 1.5 billion years after life originated (Rye and Holland, 1998; Copley, 2001). Wells strategically fails to clarify what he means by "early" when he discusses the amount of oxygen in the "early" atmosphere. In his discussion, he cites research about the chemistry of the atmosphere without distinguishing whether the authors are referring to times before, during, or after the period when life is thought to have originated. Nearly all of the papers he cites deal with oxygen levels after 3.0 billion years ago. They are irrelevant, as chemical data suggest that life arose 3.8 billion years ago (Chang, 1994; Orgel, 1998b), well before there was enough free oxygen in the earth's atmosphere to prevent Miller–Urey-type chemical synthesis.

Finally, the Miller–Urey experiment tells us nothing about the other stages in the origin of life, including the formation of a simple genetic code (PNA or "peptide"-based codes and RNA-based codes) or the origin of cellular membranes (liposomes), some of which are discussed in all the textbooks that Wells reviewed. The Miller–Urey experiment only showed one possible route by which the basic components necessary for the origin of life could have been created, not how life came to be. Other theories have been proposed to bridge the gap between the organic "building blocks" and life. The "liposome" theory deals with the origin of cellular membranes, the RNA-world hypothesis deals with the origin of a simple genetic code, and the PNA (peptide-based genetics) theory proposes an even simpler potential genetic code (Rode, 1999). Wells doesn't really mention any of this except to suggest that the "RNA world" hypothesis was proposed to "rescue" the Miller–Urey experiment. No one familiar with the field or the evidence could make such a fatuous and inaccurate statement. The Miller–Urey experiment is not relevant to the RNA world, because RNA was constructed from organic "building blocks" irrespective of how those compounds came into existence (Zubay and Mui, 2001). The evolution of RNA is a wholly different chapter in the story of the origin of life, one to which the validity of the Miller–Urey experiment is irrelevant.

WHAT THE TEXTBOOKS SAY

All of the textbooks reviewed contain a section on the Miller–Urey experiment. This is not surprising given the experiment's historic role in the understanding of the origin of life. The experiment is usually discussed over a couple of paragraphs (see Figure 2), a small proportion (roughly 20%) of the total discussion of the origin and early evolution of life. Commonly, the first paragraph discusses the Oparin-Haldane scenario, and then a second outlines the Miller–Urey test of that scenario. All textbooks contain either a drawing or a picture of the experimental apparatus and state that it was used to demonstrate that some complex organic molecules (e.g., simple sugars and amino acids, frequently called "building blocks") could have formed spontaneously in the atmosphere of the early earth. Textbooks vary in their descriptions of the atmospheric composition of the early earth. Five books present the strongly reducing atmosphere of the Miller–Urey experiment, whereas the other five mention that the current geochemical evidence points to a slightly reducing atmosphere. All textbooks state that oxygen was essentially absent during the period in which life arose. Four textbooks mention that the experiment has been repeated successfully under updated conditions. Three textbooks also mention the possibility of organic molecules arriving from space or forming at deep-sea hydrothermal vents (Figure 2). No textbook claims that these experiments conclusively show how life originated; and all textbooks state that the results of these experiments are tentative.

It is true that some textbooks do not mention that our knowledge of the composition of the atmosphere has changed. However, this does not mean that textbooks are "misleading" students, because there is more to the origin of life than just the Miller–Urey experiment. Most textbooks already discuss this fact. The textbooks reviewed treat the origin of life with varying levels of detail and length in "Origin of life" or "History of life" chapters. These chapters are from 6 to 24 pages in length. In this relatively short space, it is hard for a textbook, particularly for an introductory class like high school biology, to address all of the details and intricacies of origin-of-life research that Wells seems to demand. Nearly all texts begin their origin of life sections with a brief description of the origin of the universe and the solar system; a couple of books use a discussion of Pasteur and spontaneous generation instead (and one discusses both). Two textbooks discuss how life might be defined. Nearly all textbooks open their discussion of the origin of life with qualifications about how the study of the origin of life is largely hypothetical and that there is much about it that we do not know.

WELLS'S EVALUATION

As we will see in his treatment of the other "icons," Wells's criteria for judging textbooks stack the deck against them, ensuring failure. No textbook receives better than a D for this "icon" in Wells's evaluation, and 6 of the 10 receive an F. This is largely a result of the construction of the grading criteria. Under Wells's criteria (Wells, 2000:251–252), any textbook containing a pic-

Book	Miller-Urey/Origin of life					
	#pages	#words	corrects atmospheric compostion	experiments with updated atmospheres.	Alternate sources	Wells's grade
Schraer, W. D. and H. J. Stolze. 1999. Biology: The Study of Life, seventh edition. Prentice-Hall, Upper Saddle River, NJ. 944p.	1/2	109	No	No	No	F
Johnson, G. B. 1998. Biology: Visualizing Life. Holt, Rinehart &Winston, Orlando. 895p.	1	125	Yes, but does not give composition.	No	No	D
Biggs, A., C. Kapinka, and L. Lundgren. 1998. Dynamics of life. Glencoe/McGraw Hill, Westerville, OH. 1119p.	2	103 + box	No	No	No	D
Miller, K. R. and J. Levine. 2000. Biology, fifth edition. Prentice-Hall Upper Saddle River, NJ. 1114p.	1/2	134	Yes	Yes	Yes	D
Starr, C. and R. Taggart. 1998. Biology: The Unity and Diversity of Life, eighth edition. Wadsworth Publishing Company, Belmont CA. 920p.	1/4	58	Yes	Yes	Yes	F
Guttman, B. S. 1999. Biology. WCB/McGraw-Hill, Boston. 1175p.	1/4	152	No	Yes	No	F
Mader, S. 1998. Biology, sixth edition. WCB/McGraw-Hill, Boston. 944p.	1/4	82	Yes	No	No	F
Raven, P. H. and G. B. Johnson. 1999. Biology, fifth edition. WCB/McGraw-Hill Boston. 1284p.	2/3	194	Yes	No	No	F
Cambpell, N. A., J. B. Reese, and M. G. Mitchell. 1999. Biology,fifth edition. Benjamin Cummings, Menlo Park, CA. 1175p.	1 +1/4	330 +56	Yes	Yes	Yes	D
Futuyma, D. 1998. Evolutionary Biology. Sinauer Associates, Sunderland, MA. 761p.	1 1/3	129	No	No	No	F

Figure 2. *Textbook treatments of the Miller–Urey experiment. Textbooks are listed in order of increasing detail (AP/College textbooks highlighted; note that Futuyma is an upper-level college/graduate textbook).*

ture of the Miller–Urey apparatus could receive no better than a C, unless the caption of the picture explicitly says that the experiment is irrelevant, in which case the book would receive a B. Therefore, the use of a picture is the major deciding factor on which Wells evaluated the books, for it decides the grade *irrespective of the information contained in the text*! A grade of D is given even if the text explicitly points out that the experiment used an incorrect atmosphere, as long as it shows a picture. Wells pillories Miller and Levine for exactly that, complaining that they bury the correction in the text. This is absurd: almost all textbooks contain pictures of experimental apparatus for any experiment they discuss. It is the text that is important pedagogically, not the pictures. Wells's criteria would require that even the intelligent design "textbook" *Of Pandas and People* would receive a C for its treatment of the Miller–Urey experiment.

In order to receive an A, a textbook must first omit the picture of the Miller–Urey apparatus (or state explicitly in the caption that it was a failure), discuss the experiment, but then state that it is irrelevant to the origin of life. This type of textbook would be not only scientifically inaccurate but pedagogically deficient.

WHY WE SHOULD STILL TEACH MILLER–UREY

The Miller–Urey experiment represents one of the research programs spawned by the Oparin-Haldane hypothesis. Even though details of the model for the origin of life have changed, this has not affected the basic scenario of Oparin–Haldane. The first stage in the origin of life was chemical evolution. This involves the formation of organic compounds from inorganic molecules already present in the atmosphere and in the water of the early earth. This spontaneous organization of chemicals was spawned by some external energy source. Lightning (as Oparin and Haldane thought), proton radiation, ultraviolet radiation, and geothermal or impact-generated heat are all possibilities.

The Miller–Urey experiment represents a major advance in the study of the origin of life. In fact, it marks the beginning of *experimental* research into the origin of life. Before Miller–Urey, the study of the origin of life was merely theoretical. With the advent of "spark experiments" such as Miller conducted, our understanding of the origin of life gained its first experimental program. Therefore, the Miller–Urey experiment is important from an historical perspective alone. Presenting history is good pedagogy because students understand scientific theories better through narratives. The importance of the experiment is more than just historical, however. The apparatus Miller and Urey designed became the basis for many subsequent "spark experiments" and laid a groundwork that is still in use today. Thus it is also a good teaching example because it shows how experimental science works. It teaches students how scientists use experiments to test ideas about prehistoric, unobserved events such as the origin of life. It is also an interesting experiment that is simple enough for most students to grasp. It tested a hypothesis, was reproduced by other researchers, and provided new information that led to the advancement of scientific understanding of the origin of life. This is the kind of "good science" that we want to teach students.

Finally, the Miller–Urey experiment should still be taught because the basic results are still valid. The experiments show that organic molecules can form under abiotic conditions. Later experiments have used more accurate atmospheric compositions and achieved similar results. Even though origin-of-life research has moved beyond Miller and Urey, their experiments should be taught. We still teach Newton even though we have moved beyond his work in our knowledge of planetary mechanics. Regardless of whether any of our current theories about the origin of life turn out to be completely accurate, we currently have models for the processes and a research program that works at testing the models.

HOW TEXTBOOKS COULD IMPROVE THEIR PRESENTATIONS OF THE ORIGIN OF LIFE

Textbooks can always improve discussions of their topics with more up-to-date information. Textbooks that have not already done so should explicitly correct the estimate of atmospheric composition, and accompany the Miller–Urey experiment with a clarification of the fact that the corrected atmospheres yield similar results. Further, the wealth of new data on extraterrestrial and hydrothermal sources of biological material should be discussed. Finally, textbooks ideally should expand their discussions of other stages in the origin of life to include PNA and some of the newer research on self-replicating proteins. Wells, however, does not suggest that textbooks should correct the presentation of the origin of life. Rather, he wants textbooks to present this "icon" and then denigrate it, in order to reduce the confidence of students in the possibility that scientific research can ever establish a plausible explanation for the origin of life or anything else for that matter. If Wells's recommendations are followed, students will be taught that because one experiment is not completely accurate (albeit in hindsight), everything else is wrong as well. This is not good science or science teaching.

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