Where Do We Come From?

A Humbling Look at the Biology of Life's Origin

The origin of life on Earth is a fundamental scientific question, but we do not know as much as many biology textbooks would like you to believe.

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Science is about answering questions regarding the natural world in a rational, evidence-based manner. One commonly accepted component of the scientific method is repeatability of the phenomena under investigation. Here lies perhaps the most difficult aspect of the quest for knowledge of the origin of life on Earth. It is clearly a question about the natural world, in fact perhaps one of the ultimate questions (together with the origin of the universe itself). Yet the events we are attempting to investigate are by definition unique. Life may well have originated multiple times in the universe, including perhaps in our galactic neighborhood. But at the moment we only have one example to go by. Earth is the only place that we know for certain harbors life as we conceive it.

Before entering into a skeptical evaluation of the heart of the problem, let us answer an even more fundamental question: Why do we care? I suggest two reasons. First, should we arrive at the conclusion that life originated elsewhere in the universe and was then somehow "imported" to Earth, this would automatically imply the existence of life as a widespread phenomenon in the cosmos, and therefore the fact that living beings are not unique to our planet; it is hard to conceive of a more compelling blow to anthropocentrism since Copernicus and Galileo swept Earth away from the center of the universe a few centuries ago. Second, and perhaps more relevant, humankind would finally have an answer to the question "where did we come from?" which, like it or not, has been vexing our philosophy, art, and science since the beginning of recorded history (and probably much earlier than that). If that doesn't sound to you like enough of a reason to ponder the controversy over the origin of life, your curiosity-neurons are definitely in need of some therapy.

Couldn't We Just Look at the Simplest Organism?

Before we begin to discuss the varied theories about the origin of life, let us clear the field from one misconception. There is no such thing as a modern-day "primitive" organism that we can examine to tell what our earliest ancestors looked like. True, there are plenty of "simple" organisms around today, from viruses to bacteria to slime molds. But slime molds are in fact eukaryotes, i.e., their cellular structure and metabolism are basically similar to those of an animal or a plant. They are far too complex for our purposes. Bacteria are prokaryotes, that is, their cells are indeed simpler than those of most other living organisms. But bacteria have been around for more than three billion years, and they have become perfect reproductive machines, characterized by an incredibly efficient metabolism and ability to withstand environmental changes. After all, it is not by chance that they have proliferated for so long. So that answer is unsuitable as well. Finally, viruses are indeed among the simplest living creatures in existence, so simple in fact that some biologists even doubt that they really qualify as "living." But evolutionarily speaking, viruses are late arrivals on the Darwinian stage. Viruses are short pieces of nucleic acids wrapped in a protein. They originated from pre-existing nucleic acids, live only inside cells, and depend entirely on the host's metabolism to reproduce. Quite obviously, since our problem is to understand how the *first* living organisms came about, we cannot utilize as a model something that cannot survive outside an already existing cell. No, we are looking for something simple, yes, but self-sufficient, and *really* primitive.

Top ten classical readings on the origin of life

- A.I. Oparin, 1938. *The origin of life on Earth.* Macmillan. Oparin's pioneering suggestions about the first steps of life and the role of coacervates in forming the first cells.
- E. Schrodinger, 1947. *What is life?* Macmillan. The first physicist who had a brilliant idea about the answer to the ultimate question.
- S.L. Miller, 1953. "A production of amino acids under possible primitive earth conditions." *Science* 117:528–529. The original article on how to make the soup.
- S.W. Fox, 1960. "How did life begin?" *Science* 132:200–208. Although his theory of proteinoid microspheres as the precursors of modern cells is hard to believe, it is still cited in modern textbooks.
- F. Hoyle and C. Wickramasinghe, 1978. *Lifecloud.* Harper and Row. All about Hoyle and Wickramasinghe's interstellar theories. Turn your skeptic sense very high!
- D. Gish, 1979. *Evolution? The fossils say no!* Creation-Life Publishers. If you really want to know prima facie what the creationists say.
- F. Crick, 1981. *Life itself.* Simon and Schuster. The eclectic Nobel laureate's offbeat take on the origin question.
- A.G. Cairn-Smith, 1985. *Seven clues to the origin of life.* Cambridge University Press. For the aficionados of the clay theory.
- J.B.S. Haldane, 1985. "The origin of life," in *On being the right size and other essays,* Oxford University Press. The original soup can be found here (note that this is a reprint of a much older article).
- R. Shapiro, 1986. *Origins: A skeptic's guide to the creation of life on Earth.* Summit. Expressly for skeptics!

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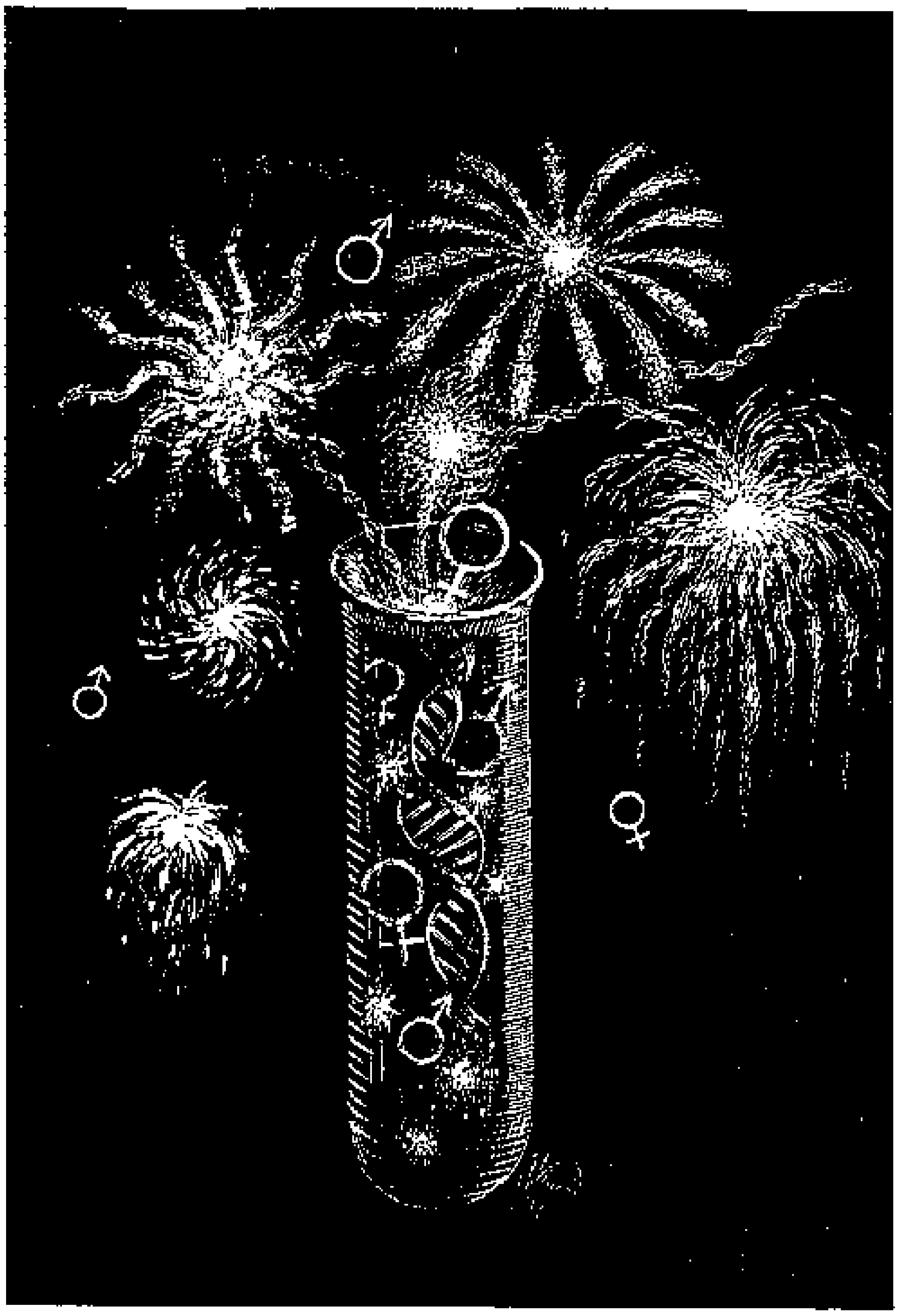
The Alternative Answer: What About God?

No serious scientific discussion of any topic should include supernatural explanations, since the basic (and very reasonable) assumption of science is that the world can be explained entirely in physical terms, without recourse to divine entities. However, as Sherlock Holmes said, "When you have eliminated the impossible, whatever remains, *however improbable,* must be the truth" (in Arthur Conan Doyle's *The Sign of Four*). So, should it turn out that we really do not have a clue about the origin of life, we must entertain other, more esoteric possibilities.

Furthermore, in the specific case of the origin of life, even such scientists as the British astrophysicist Fred Hoyle have gone on record precisely suggesting a supernatural beginning to all life on Earth. Hoyle, together with his colleague Chandra Wickramasinghe, suggested that a sort of silicon-chip creator actually goes around the universe sprinkling the seeds of life here and there. An alternative scenario is the one advanced by creationists such as Duane Gish. In Gish's case, of course, we have the classical God of the Bible, who created the universe and humankind with a very personal touch, and did so in the span of only six days. Let me make clear that a rejection or falsification (to the extent that it is possible) of these hypotheses does not prove the nonexistence of every God, which in and of itself is outside the realm not only of science, but of any human enterprise. However, modern science is certainly in a position to reject specific hypotheses about special creation. Namely, Gish's contention of a 6,000-year-old Earth is out of the question given what we know about the geology and geophysics of planetary evolution.

Should a skeptic reject outright any possibility of special creation of life? Well, no. Although implausible, it is still possible. There are two points that must be borne in mind, however, before going for a Hoyle-like explanation of the origin of us all. First, it has to be true that we really don't have a clue about how life *on Earth* originated by natural means. As we will see, though the situation is messy, it is not that desperate. Second, the mere fact that we cannot currently (or even ever) explain something does not constitute *positive* evidence for a supernatural explanation. After all, for a long time we did not know what natural phenomena could cause lightning, but eventually theories based on Zeus's anger did turn out to be incorrect. Consequently, it may be that the only rational position for the time being is simply a provisional and salutary "I don't know."

Gerald Fried



Out of This World?

The next class of explanations about the ultimate provenance of life is that—as any good old-fashioned science fiction movie of the 1950s would have proclaimed—it is not of this world. Interestingly, Hoyle and Wickramasinghe have made their contribution in this realm too, by suggesting that life was brought to this planet courtesy of an interstellar cloud of gas and dust, or perhaps by a comet. Yet another British scientist (and also an ex-physicist—coincidence?), the Nobel laureate Francis Crick, joined the ranks of the extraterrestrialists. Crick suggested a scenario that envisions extraterrestrial beings "seeding" the galaxy, much in the same fashion of Hoyle's silicon-chip creator.

Contrary to the supernatural explanations, the Hoyle-Wickramasinghe theory (but not Crick's) is at least in principle open to experimental verification, in that it makes some relatively precise predictions. For one thing, we should find plenty of organic compounds in interstellar clouds, inside comets, or both. Both these expectations have been superficially verified. I say superficially because the kind of compounds found by astronomers in these media are very simple, much too simple to provide any meaningful "seed" for the origin of carbon-based life forms on Earth. Furthermore, extraterrestrial organic compounds have random chirality, unlike the organic compounds typical of living organisms. Chirality is a property of any chemical structure that deals with the three-dimensional arrangement of its atoms and molecules. All amino acids, for example, the building blocks of proteins, can in theory come in two versions, which are mirror images of each other. These are called "left-" and "right-" handed forms, and they are characterized by exactly the same chemical properties. The biomolecules used by terrestrial organisms, however, are either left- or right-handed (depending on the type of molecule). If indeed life had come from space, one would expect to find a similar chiral asymmetry in space matter as well.

A second crucial objection to the life-from-space hypothesis is posed by its violation of the principle of uniformitarianism. If comets and meteors brought us—literally—to Earth a few billion years ago, why are they not doing it now? Meteors continue to bombard our planet and our neighbors in the solar system on a regular basis, yet so far not a single living organism or complex organic molecule has been found inside any of them. There is no reason to think that the primordial "shower of life" has ceased. Even though the conditions for the persistence of primordial life on our planet may no longer hold, presumably the space surrounding our solar system has not changed that much, leaving Hoyle, Crick, and others with a major hole in their arguments.

Finally, it has to be realized that even if we do admit that life originated outside Earth and was then imported here, we really would not have an answer to *how* life started. We would have simply shifted the question to a remote and very likely inaccessible realm, an intellectually unsatisfactory state of affairs.

The Chicken or the Egg in the Soup?

Having excluded—at least temporarily—Gods and extraterrestrials, we are left with plain old biochemistry and biology to give us clues to the origin of life. The history of scientific research in this field is long and fascinating. It started in the 1920s with the Russian scientist Alexander Oparin and his "coacervates," blobs of organic matter (mostly containing sugars and short polypeptides), supposedly the precursors of modern cells. It was Oparin, together with the British biologist J.B.S. Haldane, who came up with the idea of a "primordial soup"—the possibility that the ancient oceans on Earth were filled with organic matter formed by the interaction between the atmospheric gases and energy provided by volcanic eruptions, powerful electric storms, and solar ultraviolet radiation.

Science had to wait until the 1950s for Stanley Miller to actually attempt to experimentally reproduce the soup. The story is well known: Miller started with a reasonable facsimile of the ancient atmosphere, mostly methane and ammonia, with no oxygen. Atmospheric oxygen, together with the ozone that blocks ultraviolet radiation, was in fact produced much later by the organic process of photosynthesis in blue-green algae (however, more recent research has suggested the presence of some oxygen in the original atmosphere). Miller put the whole thing in a ball, gave it an electric charge, and waited. He found that amino acids and other fundamental complex organic molecules were accumulating at the bottom of his apparatus. His discovery gave a huge boost to the scientific investigation of the origin of life. Indeed, for some time it seemed like creation of life in a test tube was within reach of experimental science. Unfortunately, such experiments have not progressed much further than their original prototype, leaving us with a sour aftertaste from the primordial soup.

Oparin and Miller, as well as other early researchers such as Sidney Fox, thought that the problem was how to explain the appearance of proteins, since they must have caused the initial spark of life. As any student of introductory biology knows, however, there are *two* major players inside every living cell: proteins and nucleic acids (such as DNA and RNA). The problem is that the structure of DNA was discovered only in 1953 (in fact, the same year of Miller's experiment), and the nature of DNA as the information carrier of the cell was little appreciated before James Watson and Francis Crick unveiled the double-helix nature of this remarkable molecule.

As a consequence of the new discoveries, the origin of life debate after the 1950s was decidedly slanted in favor of nucleic acids preceding proteins. The new discipline of molecular biology was making spectacular progress, uncovering the universal code by which the instructions for making proteins are embedded in the nucleic acids. Scientists such as Leslie Orgel, Walter Gilbert, and others therefore proposed that the egg, so to speak, came before the chicken. Some sort of primitive nucleic acid had appeared first, followed only later by proteins.

In today's biochemically sophisticated cells, proteins and nucleic acids play very distinct roles. Four such fundamental activities need to be summarized for our purposes.

1. The DNA (deoxyribonucleic acid) encodes the information that eventually gives rise to proteins.

2. The messenger RNA (or mRNA, ribonucleic acid, the same as DNA, but with an extra oxygen atom and a few other chemical differences) then carries the information to specialized structures known as ribosomes.

3. Inside the ribosomes (which, by the way, are made of both nucleic acids and proteins) the message gets translated into proteins by virtue of a second type of RNA, known as transfer RNA (tRNA). The tRNA has the peculiar ability to attach itself to the mRNA on one side and to amino acids (the blocks that make up proteins) on the other side. This way, we have a chain of mRNA that is paralleled by the forming chain of amino acids that in turn will eventually result in the final protein.

4. The proteins, most of which are enzymes, are the actual "doers" of the cellular world. They are both the building blocks of cell structures and membranes, and the builders themselves, in the form of enzymes capable of catalyzing all sorts of chemical reactions. This includes the replication of DNA and the transcription of its message into RNA—which, of course, closes the nucleic acid-protein circle.

It's clear from the above description that we are facing a classic chicken-and-egg problem. If the proteins appeared first, so that they could eventually catalyze the formation of nucleic acids, how was the information necessary to produce the proteins themselves coded? On the other hand, if nucleic acids came first, thereby embodying the information necessary to obtain proteins, how were the acids replicated and translated into proteins? It seems clear to me that the answer, although nebulous at the moment, must lie in the proverbial middle. In fact, the existence of tRNAs points to the distinct possibility of dual structures, containing both RNA and amino acids. Furthermore, the discovery by Sydney Altman, Thomas Cech, and others that some RNAs are at least partially self-catalytic (i.e., they can catalyze chemical reactions onto themselves), lends further support to the idea of a mixed origin of life. The original molecules may have been both replicators and enzymes, with the two functions slowly diverging through evolutionary time and later assigned to distinct classes of molecules. Such a Solomonic solution appeals to our sense of aesthetics as well.

Many pathways for origin of life

For those who are studying the origin of life, the question is no longer whether life could have originated by chemical processes involving nonbiological components. The question instead has become which of many pathways might have been followed to produce the first cells.

—*Science and Creationism: A View from the National Academy of Sciences*, 2nd ed., National Academy Press, Washington, D.C., 1999.

And Then What? Hypercycles and Emerging Properties

I submit that the problem of how complex organic compounds might have formed on the primordial Earth has been satisfactorily solved by Miller-type experiments (which yield similar results under a wide variety of simulated atmospheric conditions). Furthermore, there are good reasons to believe that the initial complex molecules that underwent chemical evolution were some sort of nucleic acid-protein mix such as modern-day tRNAs. But what happened after that? There is still a very large gap between a semi-catalytic, semi-replicating nucleo-protein and the first living "organism," whatever form that may have assumed.

And the exact form seems to be part of the problem. What exactly *is* life? Physicist Erwin Schrodinger asked that question precisely in such fashion in 1947. While Schrodinger's thinking led him to predict some of the properties of DNA as a necessary component of a living organism, we still have only a vague notion of the boundary between life and inert matter. And so it *should* be, if we accept the idea that living organisms are made of inert matter that happens to acquire some "emergent properties" when it is assembled in particular ways. To put it another way, living beings are *not* separated from the rest of the universe by some mysterious force or vital energy.

How then do we know what is life and what is not? We can derive a list of attributes, some of which can be properties also of non-living systems, but with the ensemble defining a living organism:

• Ability to replicate, giving origin to similar kinds (*reproduction*)

• Ability to react to changes in the environment (*behavior*, not just limited to the special meaning that the word has in animals)

• *Growth* (i.e., reduction of internal entropy at the expense of environmental entropy—note that even single cells grow immediately after reproduction, so this is not a property restricted to multicellular life)

• *Metabolism* (i.e., capacity of maintaining lower internal entropy, including the ability of self-repair)

How did we get from a nucleo-protein to an entity capable of all of the above? And what did this entity (sometimes known as the "progenote") look like? There are very few even tentative answers to these questions, and this—I think—is where the real problem of the origin of life lies. The German scientist Manfred Eigen has proposed a possible scenario that invokes what he called "hypercycles." We can think of a hypercycle as a primitive biochemical pathway, made up of self-replicating nucleic acids and semi-catalytic proteins that happen to be found together in pockets within the primordial soup. It is possible to imagine that some of these hypercycles are made of elements that "cooperate" with each other, i.e., the product of a component of the cycle can serve as the substrate for another. Different hypercycles could have coexisted before the origin of life, and they would have competed for the ever-decreasing resources within the soup (the resources were decreasing because the hypercycles were using up some organic compounds at a higher rate than they were formed by comparatively inefficient inorganic processes). Eventually, this competition would have favored more and more efficient hypercycles, where the "efficiency" would be measured by the ability of these entities to survive and reproduce, that is by the parameters of Darwinian evolution. Life as we know it (sort of) would have begun.

Eigen and modern followers of complexity theory also expect these systems to become more complicated with the

Top ten contemporary readings on the origin of life

B.E.H. Maden, 1995. "No soup for starters? Autotrophy and the origins of metabolism." *Trends in Biochemistry* 20:337–341. A short review of recent alternatives to the soup based on the clay hypothesis, i.e., on an initial biochemistry without either enzymes or nucleic acids.

E. Stackebrandt and F.A. Rainey, 1995. "Partial and complete 16S rDNA sequences; their use in generation of 16S rDNA phylogenetic trees and their implications in molecular ecological studies." *Molecular Microbial Ecology Manual*, edited by A.D.L. Akkermans, J.D. Van Elsas, and F.J. De Bruijn. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 1–17. Though not directly related to our main topic, this article summarizes how molecular biologists can use and compare currently existing sequences of DNA to infer a wealth of information on a wide range of biological phenomena, including clues to the first stages of biological evolution on the planet.

G. Ertem and J.P. Ferris, 1996. "Synthesis of RNA oligomers on heterogeneous templates." *Nature* 379:238–240. A technical discussion of what kind of self-catalytic RNA one can expect to form in the soup.

P. Forterre, 1996. "A hot topic: the origin of hyperthermophiles." *Cell* 85: 789–792. Hyperthemophiles are bacteria that live under very high temperatures (up to 110°C). They are by all accounts the most ancient form of life still with us. The article discusses their biology as well as how much light (if any) they shed on the possibility that life arose under hot, non-soup-like conditions.

A. Laczano and S.L. Miller, 1996. "The origin and early evolution of life: prebiotic chemistry, the pre-RNA world, and time." *Cell* 85:793–798. A review of recent advances in the field by one of the originators of the modern scientific investigation into the problem (Miller, that is).

D.H. Lee, J.R. Granja, J.A. Martinez, K. Severin, and M.R. Ghadiri, 1996. "A self-replicating peptide," *Nature* 382:525–528. This article reports the discovery of what was thought until recently impossible: a self-replicating protein! Together with the earlier discovery of self-replicating RNA, this really re-opens the entire chicken-and-egg question.

E. Melendez-Hevia, T.G. Waddell, and M. Cascante, 1996. "The puzzle of the Krebs citric acid cycle: assembling the pieces of chemically feasible reactions, and opportunism in the design of metabolic pathways during evolution." *Journal of Molecular Evolution* 43:293–303. By examining the possible evolution of one of the biochemical cycles common to all living beings, the authors propose a general theory of how biochemical reactions could get increasingly complex during evolutionary time.

S. Lifson, 1997. "On the crucial stages in the origin of animate matter." *Journal of Molecular Evolution* 44:1–8. A discussion of what successive stages might have led from inanimate to animate matter. Natural selection, first at the chemical then at the biological level, is hypothesized to have played a pivotal role from the beginning.

S.L. Miller, 1997. "Peptide nucleic acids and prebiotic chemistry." *Natural Structural Biology* 4:167. Miller's recent defense of a mixed origin (nucleic acid-proteins) model for the origin of life.

M.R. Edwards, 1998. "From a soup or a seed? Pyritic metabolic complexes in the origin of life." *Trends in Ecology and Evolution*, 13(5):178–181. An exploration of a mineral alternative to the soup.

addition of new components to the cycle. From time to time the addition of one component would modify the whole system dramatically, giving it properties that the previous group did not possess (sort of like adding an atom of oxygen to two of hydrogen and suddenly getting something completely distinct and more complex: water). Complexity theorists such as Stuart Kauffman and Christopher Langton have demonstrated, on the basis of mathematical models, that some self-replicating systems can display unexpectedly complex patterns of behavior. The textbook example of this phenomenon is the so-called cellular automata, mathematical entities first imagined by John von Neumann in 1940 and that can now be studied at leisure by anybody who has a personal computer and a copy of a game aptly called "Life."

The general path leading to the origination of life seems to have been something like this:

1. *Primordial soup* (simple organic compounds formed from atmospheric gases with the aid of various sources of energy)

2. *Nucleo-proteins* (similar to modern tRNAs)

3. *Hypercycles* (primitive and inefficient pathways, emergent properties)

4. *Cellular hypercycles* (more complex cycles, eventually enclosed in a primitive cell made of lipids)

5. *Progenote* (first self-replicating, metabolizing cell, possibly made of RNA and proteins, with DNA entering the picture later on)

How plausible is all this? It certainly is conceivable from the standpoint of modern biology. The problem is that each step is difficult to describe in detail from a theoretical standpoint, and so far (with the exception of the formation of organic molecules in the soup) has proven remarkably elusive from an empirical perspective. It looks like we have several clues, but the overall puzzle is proving to be one of the most difficult for scientific analysis to solve. The chief reason for such difficulty could be—as I mentioned earlier—that all we have is one example to go by. Or it may simply be that the events in question are so far remote in time that there is very little we can be certain about, making any attempt at empirical investigation hopelessly vague. Consider that the fossil record shows completely formed, "modern-looking" bacterial cells a few hundred million years after the formation of Earth—about 3.5 billion years ago. This tells us that whatever happened before that happened quickly, but there is no record of it. Finally, it could very well be that we are missing something fundamental here. It may be that the study of the origin of life has not yet seen its Einstein or Darwin, and that things are going to change just around the corner, or never.

Top ten Web sites on the origin of life

http://users.aol.com/chinlin3/home.htm
A page devoted to the astronomical, chemical, and biological aspects of the problem.

http://eis.jpl.nasa.gov/origins/index2.html
This is NASA's "Origins" program page. It deals with much more than the origin of life on Earth, including the existence of other solar systems and the very birth of the universe.

http://www.panspermia.org/
Devoted to the panspermia theory (life imported from outer space). It includes discussions of neodarwinism and of philosophical aspects of the origin of life question. Nice pictures.

http://www.seti.org/seti-top.html
The page of SETI (Search for Extra-Terrestrial Intelligence). Lots of educational material, bibliographic references, and links. There is even a gift shop!

http://www.sigmaxi.org/amsci/articles/95articles/cdeduve.html
An article on the origin of life published in the electronic version of *American Scientist*, a magazine worth checking out in and of itself.

http://www.exobiology.nasa.gov/
The very cool NASA site on exobiology (the study of life outside our planet).

http://www.chron.com/content/interactive/space/news/mars/
Devoted to the red planet and the possibility of life on it. Extensive links and NASA press releases.

http://bolero.gsfc.nasa.gov/~odenwald/ask/alife.html
A cute NASA Question and Answer page on life in the universe, its origin, and its evolution.

http://www.sciam.com/askexpert/biology/biology15.html
A "*Scientific American*—Ask the Experts" site where James Ferris of the Rensselaer Polytechnic Institute in Troy, New York, gives concise but up-to-date information on what we know about the origin of life. Some good links provided.

http://www.santafe.edu/sfi/publications/Bulletins/bulletin-summer97/turning.html
An article from the controversial but stimulating Santa Fe Institute, devoted to research on complexity theory. It deals with Mars and self-replicating proteins.

From Dust to Dust . . .

A contemporary discussion of the question of the origin of life cannot be complete without the inclusion of A.G. Cairns-Smith's theory of clay crystals. I hope this will not be the case for much longer (except as a footnote of historical value). Don't get me wrong, I am familiar with Cairns-Smith's research and writing, and I find it excellent. But everybody can make a mistake, and I think the clay theory clearly falls within the cracks of Cairns-Smith's career, as ingenious and superficially enticing as it may be.

Briefly, the idea is that life didn't originate with *either* nucleic acids *or* proteins. The original replicators and catalyzing agents were actually crystals found everywhere in the clay that lay around the primitive Earth. There are four cardinal points of Cairn-Smith's hypothesis. First, crystals are structurally much simpler than any biologically relevant organic molecule. Second, crystals grow and reproduce (i.e., they can break because of mechanical forces, and each resulting part continues to "grow"). Third, crystals carry information and this information can be modified. A crystal is a highly regular structure, which tends to propagate itself (therefore, it carries information). Furthermore, the crystal can incorporate impurities while it's growing. These impurities alter the crystal's structure and can be "inherited" when the original piece breaks (hence, the information can be modified). Fourth, crystals have some minimum capacity of catalyzing (i.e., accelerating) chemical reactions.

Cairns-Smith then proposed that these very primitive "organisms" started incorporating short polypeptides (proto-proteins) found in the environment—presumably in the soup—because they enhanced the crystals' catalyzing abilities. The road was suddenly open for an increase in the importance of proteins first, and then eventually of nucleic acids, until these two late arrivals on the evolutionary scene completely supplanted their "low-tech" progenitor, and gave origin to the living organisms that we know today.

What is wrong with this picture? First of all, Cairns-Smith seems to completely ignore what a living organism is to begin with. For one thing, crystals don't really have a metabolism, not in the sense defined above for living organisms. The reason for this may have something to do with the fact that not only are crystals structurally much less complex than a protein or a nucleic acid, but also with their silicon-based chemistry, recognizably much simpler than the carbon-based chemistry utilized by living organisms on Earth. The lower complexity and simpler chemistry may be insurmountable "hardware" obstacles to the origination of a true metabolism in clay matter. Second, crystals don't really react to their environment either, another hallmark of every known living creature. Notice that this is a property distinct from metabolism, in that metabolism can be entirely internal, with no reference to the outside world (except for some flux of energy that must come into the organism to maintain its metabolism). On the other hand, living organisms universally and actively respond to changes in external conditions, for example by seeking sources of energy or by avoiding dangers. Furthermore, an argument can be made that crystals are not actually capable of incorporating new information in their inherited "code," unlike what happens with mutations in living beings. True, they can assimilate impurities from the environment and "transmit" such "information" to their "descendants" for some time; but these impurities do not get replicated, they need continually to be imported from the outside, and they do not become a permanent and heritable part of the crystal. Moreover, impurities do not create new types of crystals, the way mutations give rise to entirely new kinds of animals and plants.

Another colossal hole in the clay theory is—of course—that we have no clue to how the "mutiny" of nucleic acids and proteins actually occurred, and in fact we are given very faint hints about how a crystal could possibly co-opt a polypeptide to enhance its growth. Therefore, as much as creationists might like the flavor of a theory of the origin of life in which the first living beings came literally from dust (although Cairns-Smith is certainly no creationist), we're still left with ribonucleo-proteins as our best, albeit fuzzy, option. The origin of life is one question that science will be pondering for some time to come, and skeptics should be wary of oversimplified answers found in introductory biology textbooks.

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