BIOGENESIS

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ABSTRACT

This account of genesis begins with the properties of life and shows how these properties can originate as matter increased in complexity from simple gases to cells.

Although these cells were undeveloped to begin with, they were continuously refined and improved by evolution through natural selection. Thus, as time passed, they became better and better at living, but, paradoxically, this created problems that threatened the continued existence of life. First an energy crisis developed when cell populations exceeded the resources available to support them. Then an information crisis arose because further evolutionary advances required error free reproduction.

Photosynthesis evolved in response to the energy crisis. It transformed simple renewable resources into complex nutritional materials. But just as importantly, photosynthesis produced oxygen and that gas gave a strong and a new impetus for the evolution of larger and more complex cells. Then, to solve the information crisis created by the response to the oxygen initiative, cells evolved DNA. Once both of these adaptations were well established, the results were inevitable: further increase in complexity accompanied by the evolution of the broadly diverse range of species. And, eventually, even the mind emerged to endow matter with its most remarkable dimension, the ability to comprehend itself.

PROLOGUE

We need to know about where we came from and how we got here to better see who we are and where we are heading. We humanists need to root our convictions more deeply to hold against a world that has become increasingly cold and hostile.

Nations continue to take aim at each other. World leaders endorse cruel and unspeakable punishments of their dissident citizens. At this very moment developers are chopping down the trees in the Amazon Basin. Their efforts eradicate thousands of species every year as habitats are destroyed. Since the world now has fewer trees in one of its wettest places, less moisture is pumped into the air, and, as a result, global patterns of rainfall could be altered forever.

Some of the greatest of the classical forests of the world are shriveling, lakes are poisoned, fjords soured, and still the rains continue to carry down acid. Thousands know more about the drivel in the TV series, *DALLAS,* than about the many more out in the world who will go blind from vitamin A deficiency.

Holy wars rage in the Khyber Pass and around the Persian Gulf. The faithful are called to prayer from minarets that tower over Baghdad in Iraq and Dearborn in Michigan. The Mullahs run Iran. Fanatics take innocent hostages off the streets, hijack airplanes, leave bombs in restaurants, and murder innocent citizens.

You can dial a prayer at any time, or work your Sunday around any number of the TV pulpits anchored by high-tech preachers. **In** the name of God, these bible-thumpers censor textbooks, ban novels, coerce school boards, legislate the teaching of biblical creation, ban homosexuals, excoriate secular humanists, and take your money away.

We humanists have not lit up the sky. Religious fundamentalism has grown stronger than ever. Compassion, justice, and the sense of humanity have gone out of style.

IT IS TIME FOR A NEW ORDER

E. O. Wilson, who is an important sociobiologist, has argued eloquently for a new order of enlightenment ... "the mental processes of religious belief ... represent programmed predispositions whose self-sufficient components were incorporated into the neural apparatus of the brain by thousands of generations of genetic evolution. As such they are powerful, ineradicable, and at the center of human existence." I Wilson then suggests a way out: that scientific humanism be modified to accommodate modern natural science. He believes that the energies now heating up those prayer meetings can be "shifted in new directions when scientific materialism is accepted as a more powerful mythology... transition will proceed at a more accelerating pace. Man's destiny is to know, if only because societies with knowledge culturally dominate societies that lack it." [2]

Sociobiologists argue that religions had survival value. There was a time in prehistory when belonging to a group offered more protection than not belonging. I suppose that those who stood up to be counted behind their leaders received the kind of preferential treatment that contributed to their survival: perhaps a distribution of meat, a better piece of land, or the benefits from the sacrifices of the altruistic few among them. Sociobiologists might then go on to say that people make such choices under the direction of special genes, and once those choices were made again and again in successive generations over millennia, more persons with those genes would increase in the population. That is why most persons today identify with one or another of the main religions. They carry more "church genes."

To continue the argument, the sociobiologists would say that knowledge has greater survival value than belief. For example, what shaman could use insulin; where, in either of the Testaments, in the Koran, and the like, do we find the recipe for the smallpox vaccine, the cause for cholera, and the enunciation of Heisenberg's uncertainty principle. Those who know are presumed to have an edge over those who do not (or would not) know, and, somehow, they will begin the long process of replacement of the "church genes" with the "unchurched" ones. I am convinced that such a replacement will be a long process. Those "church genes" must be very firmly implanted.

Many humans would still rather believe than know despite the promise of eventual enlightenment. The scientific enlightenment that has changed the world has not succeeded so well with minds: the belief in astrology and Ouidja boards in predicting or controlling human destiny is stronger than ever. Far too many rely on the portents revealed in seances, and the directives from bio-rhythms. They yield to faith healers, snake oil, and the likes of Jeremy Rifkin.3 Many people simply do not trust scientists. They blame scientists for everything that is bad, from the spoiling of the environment to the Challenger and the Chernobyl catastrophes.

Nevertheless, there is still hope. Although we are fewer, we can make a difference in the way the world can go, and an important aspect of our ability to sustain will come from the power to know and accept the inevitable realities of existence: who we are, where we came from, where we sit in the universe.

One of the most important places to continue the approach to these realities is in biogenesis: the scientific story of the origin of life. It is very important to be realistic about explaining ourselves, and to know how we relate to everything. The ancient leaders knew this, and so have erected the myths and the great epics to insure that they would gather and hold onto followers. Imagine, if you can, the attraction of the myths that were so powerful that they could "explain" where we came from in convincing stories and with language so satisfying that the myths would be accepted and certified on faith alone. Today, the tellers of such stories easily fill ballparks with believers; yesterday, they rallied the populace to saddle up and go after the infidels, the righteousness of their cause ringing in the the battle cry, *"Deus Volt1"4*

Biogenesis is a story with a different ring to its certification. To certify that something is valid in science requires that observations be reduced to objective explanations which must then be tested either by experiment or by historical congruence.5 This holds, of course, for the accounts of origins. Even though we cannot directly test hypotheses for the origin of life directly, we can still reconstruct past events and weave them into accounts whose plausibility rests on the depth of the supporting evidence and the level of consistency with natural laws.

But what is it that must be originated to have life? How can we speak about biogenesis without an understanding of what life is and how it lives? It is clear that we should begin with the study of life itself, its processes, composition, and organization in order to understand what must happen to matter to become alive.

> Nevertheless, not everyone needs this information. I have provided a quick way to cut through the next section for those readers who have knowledge of modern biology or for anyone who wishes to get to the origins section without delay. The main points are summarized in boxed inserts (like this one).

LIFE

It is an inherent property of matter to become alive. A supernatural force was not needed to coax the man from the mound of dust, nor to pull the woman from the rib. All that was necessary was for matter to interact with the conditions already present on earth, and life would eventually begin. Then once it began, evolution would take care of the rest, moving the living substance inexorably forward, unfolding its potentials to form the richly textured carpet of existence that led to the mind.

> "It is an inherent property of matter to become alive." But the emergence of those properties depends on conditions.

EARTH

We had to begin somewhere in the universe where the conditions were ripe and this planet is a good example to show what those conditions were and how they developed. The planet Earth was assembled four and one half billion years ago along with the other planets from the matter left over after the sun was formed.

Earth was close enough to sun to be warmed sufficiently to maintain water as a liquid, and not so close as to boil it off. The distance from the sun also determined its composition. Earth came to be made of a greater proportion of the heavier elements (comparable to the silicon in sand; and the iron in hemoglobin) having given off most of the lightest elements (such as hydrogen and helium) to the planets (like Jupiter) farther away. The result was a *terra firma,* solid substance underfoot, rather than something more nebulous.

Planet Earth also turned out to be the right size to exert sufficient gravitational pull to hold both water and an atmosphere. Taken together, it was the effects of both position and size that led to the conditions which fostered life in the beginning and preserved it to the present.

We begin, therefore, with a very broad set of circumstances that happened to be present on one of the relatively small inner planets of a particular composition. We will let inanimate substances run their course for about one billion years until life emerged. But how will we know when it happened, when matter finally crossed over from the inanimate? We should be able to recognize life by its properties.

> The conditions most favorable for the origin and evolution of life on earth were determined by its size and its position in the solar system. Those conditions are: composition, temperature, and size.
> Composition: a "rocky" planet as compared with others, such as Jupiter, which is essentially gaseous.
> Temperature: the moderate climate allows water to accumulate over most of the surface as a liquid.
> Size: enough mass to exert sufficient gravity to hold gases and create an atmosphere.

LIFE PROPERTIES

Living things respond to stimuli in an organized way. "Poke it with a stick. See if it moves." Any kid will tell you that. Life also undergoes metabolism. Like a flame, the living thing must constantly transform and redirect matter and energy towards the performance of itself. It does this through its metabolism, a complex internal chemistry that escapes most ordinary citizens, but is, nonetheless, behind our every breath and is the reason behind our body heat. In the process metabolism transforms, and redirects matter and energy towards preservation for the present and the future. In short, it is by virtue of the operation of metabolism that the living condition extends itself through time, and, by definition, it is responsible for two other properties - growth and reproduction.

Therefore, we ought to be able to identify living things by their ability to respond to stimuli, grow, and reproduce. However, we will be in trouble if we do so. The properties I have named do not set life apart from nonlife, certainly not as cleanly as we need to. Flames and fountains display all the properties I have mentioned. They transform matter and energy into their own kind as if they have a kind of "metabolism." Flames and fountains respond to stimuli; flames burn hotter when fanned, fountains go higher when they are supplied at higher pressures. Besides, they will also grow and reproduce. One fire can certainly make another; most of us have seen ice crystals grow and advance across the window pane. But flames and fountains are not alive.

So it is not easy to distinguish life from nonlife. And why should it be? Life is an extension, an extraordinary appendage of the surface of earth. Matter is matter whatever it constitutes. And energy is still energy whatever it moves: wheels, hearts, minds.

But surely there must be a way to distinguish what is living. I believe that life becomes separated from nonlife by its ability to undergo evolution by natural selection.7 Anything that is alive has the potential to become something more than it was before through evolution. But what is not alive will always remain the same unless subjected to incredibly strong energies like those that exist in the interiors of stars. Thus we would not expect a lump of sugar to rise one fine day and roam the Serengeti. The lump will always be the same lump until you drop two or so into your morning coffee - and then drink it.

Evolution by natural selection operates through the genetic system. This system is a complex organization of molecules that informs organisms about themselves, who they are, and what they must do to live in the present and persist into the future. It is the means to introduce hereditable variations into offspring which, after rigorous testing by natural selection, can survive and eventually shape new species.

We will call matter alive when it takes on all these properties:

Organized response to stimuli
Transformation of energy by metabolism
Growth and reproduction
Evolution by natural selection
Cellular organization

CELLS

Cells are the fundamental organizations through which life lives. They are the seat of the life processes. We do not know of anything organized below the level of cells that still retains the capacity for independent life.

"Cells are the fundamental organizations of matter through which life lives."

All cells fall into fundamentally different categories: they are either prokaryotes or eukaryotes. There is a considerable body of evidence that suggests even a third form of life, the archaebacteria.8

The prokaryotes are represented by present day bacteria. They are smaller, simpler cells, more ancient than the eukaryotes. They lack internal partitions for the division of labor and the compartmentalization of function. Eukaryotes, on the other hand do have such internal compartments: nuclei to house DNA, mitochondria for oxidative metabolism, chloroplasts for photosynthesis, and others. Clearly, eukaryotes are more advanced because they are more complex, and it is precisely for this reason that they serve the needs of all higher forms of life. Therefore, the genesis of such complexity was a smashing breakthrough in the evolution of life, analogous to the invention of the wheel, or better yet a Promethian spark that sent matter roaring towards the pinnacle of its potentials.

All cells fall into different categories. They are either: archaebacteria, prokaryotes, or eukaryotes.

It is possible that the archaebacteria figure directly into the history and natural order of life.The archae bacteria resemble prokaryotes in their simplicity of form and absence of internal compartments. Nevertheless, they do differ biochemically, and they are believed to be more closely related to the universal ancestor of all cells than either the eukaryote and prokaryote.

Some species of these ancient cells fare very well in the harshest environments known, the very hot and salty places more representative of the primordial earth than what is generally present on the planet today. Surprisingly enough, some archaebacteria have even found their way into our own large intestine where they metabolize crude fiber and generate gas. But we are on much more intimate terms with the archaebacteria since their genes appear to be present in all of our cells.9

> The archaebacteria and prokaryotes are the smallest and simplest cells. They have no internal specializations, and they were the first to evolve.

There is good evidence that an archaebacterium was the first to evolve a nucleus and become a eukaryote. There is more evidence that at least some of the compartments in eukaryotes were once free living prokaryotes; bacteria that had been acquired through symbiosis (a mutually benefical relationship). Accordingly, the eukaryote is, in this sense, a chimera, part archaebacterium, part prokaryote. We shall return to the origin of the eukaryotes later on.

> The eukaryotes comprise all higher forms including humans. They have internal compartments specialized for the division of labor. Eukaryotes appear to be hybrids of both archaebacteria and prokaryotes, originally acquired through symbiosis.

BIOMOLECULES

In all, life must have begun through the elevation of relatively simple substances into new levels of complexity, from the inorganic matter in rocks and stones to the organic molecules which have by now become flesh and blood. These organic molecules are the biomolecules.

The biomolecules fall into four major categories: carbohydrates, lipids, proteins, and nucleic acids. Each category is built in a specific way, and each serves special functions.

Biomolecules and their functions

Carbohydrates and lipids for energy and structure
Nucleic acids for information storage and transfer
Proteins for implementation of the information in nucleic acids

The carbohydrates include the sugars and the starches which function as sources of energy designed for immediate use. But other carbohydrates (cellulose, for example, as in wood and in cotton) are mainly structural. Lipids include the fats, the oils, and the waxes. Like the carbohydrates, certain lipids are also fuels, but more efficient and specialized for long term use. Certain lipids also have structural and other specialized features. For example, not only do they make up an important part of the cell membrane, but some types of lipids also form the cores of the sex and other hormones.

PROTEINS

Proteins are entirely different from lipids and carbohydrates. You can tell from their name that these molecules are special. Protein means first and foremost. First in complexity, variety, and versatility, the proteins are first in importance. Because they can become so complex, they can serve all the varied needs of life: the matrix in resilient and shielding skin, in cable-like tendons and shafts of hair, in whites of eggs, muscles, and others. We might also include the proteins which function in filling the more subtle needs for specificity and recognition, such as those making up the antibodies and enzymes.

Proteins owe their versatility to the arrangement of their subunits, the amino acids. There are twenty different kinds of amino acids. Protein molecules take on their specific identities through the line-up of these twenty. So even though you can reduce the chicken into the same pool of amino acids as a cow, you could not reassemble the chicken again from the chicken soup unless you knew which amino acid followed which in the amino acid sequence of all the chicken's proteins.

> Proteins are composed of subunits called amino acids. The kinds of amino acids and their sequence determine the shape of protein molecules. The molecular shape determines function.

The amino acid sequence sends a message, and the message is the shape of the protein. The different amino acid sequences result in different overall configurations; hair protein is a cylinder, egg white a globule. The cylindrically shaped proteins are the structural ones. They provide the scaffolding upon which many fundamental events become organized.

Globular proteins, however, act like "workhorses" and "watchdogs." The transport of oxygen by hemoglobin is one example of what I mean by the "workhorse" analogy. The "watchdog" situation is quite different. It implies classes of molecules made to recognize and interact with others.

The recognition and interaction function of globular proteins is achieved through shapes. Recognition between two molecules occurs when they fit, and interaction can follow if the fit is close enough for the two to stick together, even transiently. Fitting and sticking can occur because the shapes are complementary, like hand and glove. In effect, therefore, proteins are synthesized with a sequence of amino acids that makes a shape complementary to the molecules it is meant to deal with.

The shapes are "read" like a primordial braille: antibodies from the immune system recognize specific classes of foreign molecules and destroy them; insulin joins with its receptor and the cell responds; the AIDS virus also recognizes the T cell via the conformation of specific cell surface proteins.

Enzymes are another group of fundamentally important proteins that operate through the fit and stick principle. They are catalysts, really biocatalysts because they are only associated with life. Enzymes accelerate the rate of chemical reactions so that the necessary reactions can take place quickly enough at the ordinary temperatures compatible with life. The temperature is the key. We could accelerate the rate of chemical reactions with heat to a point where cellular needs could be met, but that would not work either for the same reasons that a boiled egg would never hatch. Excess heat collapses protein structure.

Life could not live without enzymes. All the multitudes of life's chemical reactions are mediated by as many different enzymes, each one specific for a given reaction, just as one key is specific for one lock. There must be some kind of guarantee that the correct sequence of amino acids would be inserted into the protein structure to make the right key for each of the locks.

> Proteins function as structural agents and carriers. **In** addition, they accomplish subtle recognitions and catalysis through the fit of complementary shapes.

All proteins, fibrous and globular alike, must be nearly perfectly sequenced to function correctly, to get the message across effectively. Sequences must be preserved to maintain the identity and integrity of the species so that the chicken in the egg can be assembled from its amino acids and hatch out as a chicken, and not as a cow. Like the family jewels, all our amino acid sequences comprise our biological heritage passed down to us from the distant past after considerable reworking by the evolutionary mill. They must be transmitted into future generations for the survival of the specIes.

NUCLEIC ACIDS

Most readers have probably heard of at least one kind of nucleic acid, DeoxyriboNucleic Acid, or DNA, the famous double helix elucidated by James Watson and Francis Crick10 over thirty years ago. DNA carries the blueprint for the structure of proteins. It is also responsible for the continuity between generations because the blueprint is replicated and transmitted every time reproduction occurs. DNA is also the engine of evolution. It is changeable and thus feeds new variations into every generation to fuel natural selection.

> The nucleic acids include both DNA and RNA. They are composed of subunits called nucleotides which fall into two classes, either purines or pyrimidines.

DNA's blueprint is an integral part of its structure. The DNA molecule is composed of subunits called nucleotides. There are four such nucleotides commonly present, each one distinguished from the other by certain bases (complex carbon-nitrogen ring structures)which carried as essential parts of the nucleotides. In fact, the nucleotides are classified into two main families by two general types of bases. They are either purines (two rings) or pyrimidines (one ring). The sequence of purine and pyrimidine nucleotides along the length of DNA is not only the spine of the molecule, but it is also the blueprint. The specific sequence of nucleotides, exactly which one follows the other, turns out to be a series of code "words" which specify the line-up of amino acids in proteins. The sequence of nucleotides in DNA is also the code for its own replication, and the key to the operation of that code in both replication and protein synthesis is the principle of complementary base pamng.

> The purines and pyrimidines form complementary base pairs.

The shape of the purine is complementary to that of the pyrimidine. They form stable pairs in a manner analogous to the fit and stick of complementary shapes mentioned earlier for proteins. In the double helix, the purines of one strand pair with the pyrimidines of the other and come close enough to generate certain chemical bonds between them. This is the way both strands hold together to make the double helix. In the replication of DNA the same principle holds. Each strand acts as a template to guide the insertion of its complements according to its own line-up.

> DNA carries the blueprint for the structure of proteins. The blueprint is carried in the sequence ofits nucleotides, and the sequence is transferred by complementary base pairing for both replication and protein synthesis.

Complementary base pairing and templating are also central to the operation of DNA in protein synthesis. However, in this case, the nucleotide sequence is passed from DNA to another nucleic acid, RiboNucleic Acid (RNA), before it is copied into the corresponding amino acid sequence. The first step in the process, called transcription, involves making a complementary copy of RNA from the DNA template. Processing of the RNA then follows to yield messenger or mRNA. The nucleotide sequences on the messenger must then be converted, or, in the jargon of the molecular biologist, translated, into amino acid sequences to spell out the specific protein.

The genetic code is fundamental to this translation. The units of the code are groups of three bases called codons. Each of the unit codons is the code "word" for an amino acid. The keys to the translation of the codons into their corresponding amino acids are found in yet another group of RNA molecules known as transfer RNAs (tRNAs). There are as many tRNAs as there are amino acids. Each tRNA is specific for one amino acid, and each one bears a triplet of bases complementary to the codon for the amino acid it is designed to carry. The tRNAs, therefore, give each amino acid a specific handle by which it can be joined to its codon on the mRNA, placed in line according to the master lineup that was inherited *via* the DNA from which it was transcribed.

> Protein synthesis takes place in two general steps. First the DNA nucleotide sequence is transcribed onto RNA, and then the RNA nucleotide sequence is translated into the amino acid sequence.

Finally,the actual assembly of amino acids into the protein must occur in ribosomes. These are special structures which act as "jigs" holding everything (mRN A, tRN *AI* amino acid complexes, and others) in the precise alignment required for the bonding together of amino acids.

> "DNA is the engine of evolution. It is changeable and thus feeds new variations into every generation to fuel natural selection."

In summary, therefore, life, informed by its nucleic acids, lives through its proteins. The proteins are carefully specified to make the shapes required for their specific functions. But the amino acid sequence in the protein gives only the potential for making these shapes. The potential to make them is realized only for a certain range of conditions. Change the conditions and the shape is liable to collapse.

Recall the example I gave earlier in connection with heat and its effect on the chick embryo. Boiling changes the shape of proteins leaving them useless, but so do other factors. Chicks are ruined in their eggs by too much (or too little) salt, acid, or a variety of other agents that do not fall within a relatively narrow zone of concentrations. The point is that proteins require carefully controlled conditions to hold their all important configurations. That degree of control is assured by the organizational units in which the proteins are synthesized, the fundamental structures that control the acids, salt, and the other conditions that assure that the shapes spelled out by the genetic code will be expressed and preserved. These fundamental units are cells. We have come back again to these fundamental units and so complete the circle.

THE ORIGIN OF LIFE

An account of life's origin must tell how matter increased in complexity and organization to arrive at cells. This means assembling biomolecules and aggregating them into metabolizing units controlled by DNA, and capable of evolution. Then we shall proceed to relate how eukaryotes evolved from archae bacteria and prokaryotes.

TIME FRAME

As the oldest fossil cells appeared about 3.5 billion years ago, and as the age of the earth is estimated at about 4.5 billion years, life must have originated in one billion years. If there is any "miracle" involved in the origin of life it is simply that I will encompass those billion years in the next few moments.

Several accounts have been put forward to the account for how life could have originated over all those years. All are acceptable because each is plausible in its own way. But since direct evidence of exactly what *did* happen is difficult to obtain, we have to rely on extrapolations from the present to show what *could* have occured in the past. The plausibility of such reconstructed accounts depends upon the strength of the evidence which supports them.

Some scientists present evidence that life began as certain types of clay." Others have argued about which came first, the genetic system, or the metabolic milieu in which it is immersed. One recent hypothesis holds that the genetic system and the metabolic complex originated independently, and that life really began when a primordial metabolism was "infected" by nucleic acids.12 Other scenarios hold that life did not originate on earth at all but rode in on comets, or other objects from outer space.1 3

Any or all accounts might well have operated in biogenesis. Even though most are plausible, they do differ. But that hardly matters since the differences between them are mainly in emphasis. What does matter is that they carry the same core thesis: that life emerged from nonliving matter by invoking only its inherent tendency to increase in complexity and organization. To my way of thinking it is this central thesis that is most important, and the fact that we can construct several plausible accounts from the same foundation only serves to strengthen the base all the more.

Nevertheless, the account I will give here will reflect my own bias - that the origin of life occured here on earth. By doing so, I have not chosen to ignore any of the extraterrestrial scenarios. It is simply that I believe that the placement of the origin elsewhere than on earth begs the question, since in any case, life as we know it, had to originate on a planet very much like our own.

ORIGIN OF BIOMOLECULES

Most of the biogenetic narratives begin with the synthesis of the subunits for the complex biomolecules under conditions present on the primordial earth.

Most scientists agree that, in the beginning, the principal elements[14], the raw materials for the biomolecules (carbon, hydrogen, oxygen, nitrogen), were tied up in certain gases in the atmosphere. Most scientists also agree that the composition of the primordial atmosphere was much different from the one we have now. Nitrogen was present as ammonia, an acrid substance familiar to anyone who does serious house cleaning. It will become an important component of proteins and other important biomolecules such as the purine and pyrimidine bases. Another seminal gas was methane. Coal miners know about this one. It is a powerfully explosive agent responsible for most major mine disasters, with their attendant tragic costs in life and limb. Yet it was one of the main sources of carbon for all the biomolecules yet to come. The other main source was hydrogen.

But what about the most familiar gas, oxygen? This gas was not present in the beginning, at least as a free agent. Whatever oxygen was there was bound up in other compounds, and the lack of the free oxygen made a big difference. When bound up it could not contribute to those kinds of oxidations (fires in forests, or "fires" in muscles and brains) that release energy most effectively. When locked into other compounds, oxygen is "spent," and it will not support the aforementioned fires and "fires." Thus, the oxygen in carbon dioxide is unavailable, so much so that it is very effective in extinguishing flames wherever they occur. And the same things can be said about water, another compound with oxygen bound into the molecule. Nevertheless, *free* oxygen is abundant in the atmosphere of today. It was a late-comer, the product of life itself, and the harbinger of enormous changes in the history of earth, as you shall see later.

The primal air, therefore, was certainly acrid, dangerous, and noxious with all those ammonia, methane, and hydrogen gases around. But even without free oxygen it was extraordinarily germinal as shown in a very pivotal experiment. When the gases are reassembled in a glass-enclosed version of the primoridial earth, something quite remarkable happens. The gases will yield some amino acids, and, in addition, they will produce the precursors for the subunits of all the other biomolecules. The experiment which demonstrated the synthesis was first introduced by Stanley L. Miller[15] over thirty years ago. The same experiment can be routinely repeated by amateur scientists down in their basements with relatively simple apparatus.

The apparatus consists of a number of interconnected glass vessels containing the mixture of gases enumerated above. One of the vessels carries electrodes to shoot sparks through gases which fill the entire apparatus. The sparks are sources of electrical energy and ultraviolet light set up to simulate lightning or sunlight, common sources of energy known to have operated in the beginning. Another chamber in the apparatus held water. The system was also equipped with a cooling jacket to condense the vapors produced by boiling the water.

When in operation the electrodes were sparked through the gases as the water boiled. The boiling water sent vapors rising and circulating throughout, washing the sparked gas mixture to dissolve whatever resulted there from the searing action of the "lightning." The circulating vapors were then condensed as they passed through the cooling jacket, and allowed to accumulate as the boiling, sparking and circulating continued in operation over several weeks. A wide variety of new substances were found and when the condensate was finally analyzed, a wide variety of new substances were created. Among these were amino acids and the precursors for all the other key biomolecules.

Subunits and precursors are a long way from fully formed biomolecules. But it was a beginning, and as things turned out,some of these subunits and precursors carried the seeds of their own joining, providing the correct conditions prevailed, as illustrated in another experiment first performed by Sidney Foxl6 in the I960s. This experiment yields protein-like compounds, the proteinoids, from amino acids by some very simple manipulations, so routine in fact that they are performed in many (enlightened) high school science labs. In practice, one heaping teaspoon of dry amino acids (those obtained from the Miller apparatus) is baked on a hot rock and then washed off with a little water. The baking of the dry amino acids drives them together to make the proteinoids. But something more happens in the wash. The proteinoids form even more complex organizations.

The wash water carried proteinoids organized into globules called microspheres. These assemblies superficially resembled primitive cells. Now here is another clear demonstration that small molecules (amino acids) can be urged to form larger ones (proteinoids) by simple methods which mimic the conditions that must have existed on the early earth. First the Miller experiments assembled near-biomolecules, then the Fox experiment not only yielded proteinoids, but it also brought them to the higher, microsphere level of organization.

The spontaneous generation of complex forms under very simple conditions is called self-organization. Examples of this phenomenon vary all the way from the formation of galaxies to the construction of viruses.17 Viruses can be taken apart down to their components molecules, then, by a simple reversal procedure, repackaged to be whole and infective once more. Parts of cells (cell membranes, ribosomes, mitochondria) can be broken down too, and then reassembled with the restoration of their original functions. Indeed, even more complex organizations show the same ability to spontaneously reassemble. A living sponge, or the limb bud of a chick, can be disaggregated into a jumble. Left on their own, the sponge cells will crawl around, find their former associates and resurrect the sponge again; the different cells of the limb will also reassume their former geometry.

We may presume that such tendencies to self-assemble were played out among all the different subunits that rained down out of the atmosphere after the Miller syntheses. We can easily imagine an almost endless process of random hitting, joining, breaking, rejoining, in infinite permutations among the different products of the pre-biotic syntheses. They went racing about through the waters with greater and greater probability of hits as concentrations increased with the passage of time. Some of the assemblies persisted and gathered others to themselves becoming more and more complex as the centuries ground into millennia.

Now suppose that we postulate the involvement of lipids in the forming assemblies. Certain lipids can be readily organized into membranes of the kind we see as the dynamic boundaries around present day cells. We can make lipid membrane bounded assemblies which not only look like cells 'but which also mimic them in the performance of specific metabolic functions. Such complexes are classical models used in the study of the origins of life. They are called coacervates.[18] It is reasonable to hypothesize that coacervates formed from micro spheres, proteinoids or other assemblies of that kind.

In any event, because they were now enclosed with lipid membranes, the coacervates could go on to become uniquely different, a situation analogous to the building of fences between neighbors to keep the dog contained. The point is that new properties should emerge once membranes were in place. Membranes would become gateways, allowing certain substances to pass, while holding back others.

Thus, some of these coacervates must have been able to take in substances that others could not, and they would have grown larger by the accretion of such materials. Certain ones could also have been more efficient at this process because they happened to have held proteinoids with enzyme activity. The most efficient would grow and swell faster than the others. Pieces would break off when the coacervates grew so large that they ruptured the relatively weak membranes holding them together. If the "daughter" fragments happened to contain the "parent" enzymes they would also swell and break like those before them. And out of all the assemblies there had to be some that were still better than others, some that could incorporate more effectively, grow faster, break up with better compositions in the pieces. Selection surely operated to preserve the strong and the most stable members of the population. As usual, the race went to those best fit to survive the circumstances.

The advantage would be maintained in future generations if one or another of those coacervates happened to hit upon some kind of genetic mechanism. Then the show could really begin in earnest. No matter how crude it was to start with, Darwinian selection could then begin to operate and in time would carry the coacervates to perfection.

THE ORIGIN OF GENETIC SYSTEMS[19]

The first genetic systems are believed to have been based on RNA, not DNA. The RNA would have to begin *de novo* much like the chicken arriving without the benefit of an egg. According to present day experiments, self-propagating populations of RNA polymeres can be induced from only the nucleotide subunits and their polymerizing enzyme- *de novo* not only because no "parent" template would be needed but also because appropriate catalytic activity could have been supplied *via* spontaneously created microspheres. Alternately, if an RNA template happened to form, then self-propagating populations of RNA molecules can be obtained from it with just the nucleotides and without polymerizing enzyme. Either way - egg first, chicken later, or chicken first, egg later - seems to work.

Both of the experiments just cited demonstrate that even the most rudimentary precursors (such as those nucleotides that can be obtained from the Miller synthesis) could give rise to self-propagating populations of RNA molecules. Furthermore, it can be shown that such molecules could eventully involve themselves in protein synthesis. It is true that matters would be crude here, less certain than in today's systems. But remember that we are talking about getting started from the bare bones. And such a start would be all that is necessary once chance variation and natural selection entered to hone and refine the rudiments.

In the beginning, therefore, minimal genetic systems can be evoked out of nucleotides, and membrane bounded coacervates capable of minimum metabolism can also be assembled from proteinoids and lipids with, perhaps, some added carbohydrates. The coacervates can grow and break, undergoing a loose kind of reproduction. If the genetic systems developed together with the coacervates, or if one were "infected" by the other, the emerging coacervates would then enter a new level of organization.

LIFE AT LAST

Membrane bounded coacervates capable of a metabolism and informed with even the most primitive genetic systems have achieved a very important status. By the criteria mentioned earlier, they are now endowed with the property of life, but only minimally. The genetically informed and directed coacervates should probably be regarded as an approach to modern cellular organization, as protocells, assemblies on the way to that level of organization,but not there yet.

THE INFORMATION CRISIS

Natural selection would operate on the protocells to preserve the favorable variations and press them forward over many generations, each building upon the other to hold the edge ever sharp with the accumulation of only the best among them. Fidelity in replication was certainly essential in order for such accumulations to occur at all, otherwise the advantage that would have accumulated through what could have been thousands of generations would be lost in just one mishap, and that would be the end of the line. The requirement for accuracy in information processing, the need to develop the means to detect mismatches in base pairing, became the next impetus for natural selection.

DNA is a better candidate for error correction than RNA because it is a double helix. The width of this structure is remarkably even all along its length when all the complementary base pairs are correctly matched. Mismatches, however, leave "lumps" where they occur. Present day replicating enzymes "proofread" their work by detecting the lumps and "editing" them out, pyrimidine pairs as so many bumps in an otherwise smooth contour. Such sensing would not be possible in RNAs because these are single stranded molecules. Consequently, incorrect insertions and correspondingly incorrect sequences could get through in genetic systems based on RN A. That possibility was minimized by the replacement of the original single stranded RNAs with double helical DNA which had the potential for error correction. When DNA finally did take over, the protocells changed as the whole world would soon change. Here was a powerful new entity, comparable in a way to the cosmic egg inventions in creation myths. Protocells with DNA were the first phase of the transformation that led to the universal ancestor that gave rise to archae bacteria and prokaryotes.

THE ENERGY CRISIS

Once a genetic system reasonably free of errors was established, life must really have begun in earnest. Burgeoning populations would have seethed in the ancient seas enriched by the Miller synthesis to the status of a dilute bouillion. The protocells lived off this primordial soup, preserving and accumulating advantages with each generation to continually improve the lot. But the more efficient they became in using environmental resources to fill nutritional requirements, the more they were in trouble. As time passed and the selection processes continued, populations must have exploded, and, as their numbers continued to increase, they outstripped the capacity of the Miller syntheses to provide enough molecules. In true Malthusian fashion the soup became too thin for the numbers that depended upon it.

We can get an idea about how these early organisms went about filling their nutritional requirements by surveying what exists today. There are currently two main nutritional adaptations: heterotrophs and autotrophs. Heterotrophs, (meaning other feeders, like the animals in general), must use preformed complex organic substances, such as glucose and certain amino acids, in order to fulfill their nutritional requirements. The autotrophs (which means self-feeders) require only the simplest precursors (such as hydrogen and carbon dioxide) because they have the metabolic adaptations to make the complex organic molecules they require. Both heterotrophs and autotrophs were probably present in the early times that we are talking about, since both types are found today among the closest relatives to the most ancient cells.[20] They would have put pressure on whatever resources existed.

PHOTOSYNTHESIS

The first of the "famines" had arrived. Life was threatened at the start and we probably would not be here at all if it were not for the extraordinary plasticity and adaptability of the living substance. New strategies of autotrophy emerged in response to the heavy pressures, and the most significant among these was photosynthesis.

Photosynthesis centers on the conversion of light energy to chemical energy. Various pigments evolved to capture the light, and many cells then used the trapped energy to enrich carbon dioxide by transforming it into carbohydrate. This bit of wizardry is accomplished with electrons, by actually "lifting" them with the absorbed light energy and then storing the energized electrons onto carbon skeletons derived from carbon dioxide. The electrons are central to the process,andmust be available from an appropriate source. The actual source, exactly where the electrons came from, was to become a crucial pivot.

One of the electron sources used was the gas, hydrogen sulphide, (known also as the cause for the stench of rotten eggs). But the real breakthrough came when photosynthesic adaptations advanced far enough to use water.

The use of water turned out to be a stroke of monumental importance. It solved the energy crisis for a long time to come: water is a renewable resource, sunlight shall also last, and carbon dioxide is abundant, at least on a global scale. But just as importantly, the use of water for photosynthesis led to the liberation of the oxygen carried in the water molecule, and once it was free, the gas changed the atmosphere and cleared the way for the major ascent to the highest forms of life.

OXYGEN

Oxygen interacted with sunlight to form ozone in the upper atmosphere, and that profoundly affected conditions on the earth below. Before ozone, the colonization of land was impossible because the ultraviolet radiation streaming down from the sun was lethal. The advent of oxygen, however, changed everything since the ozone blocks out ultraviolet radiation. Thus, when sufficient ozone formed, organisms could move onto land and be safe under its umbrella.

In addition, the Miller synthesis of organic compounds would be extinguished because one of its main energy sources, the ultraviolet radiation, was no longer available. Furthermore, any of the organic substance that had accumulated would be rapidly oxidized by the oxygen in the atmosphere. Thus the cells which depended upon the products of those syntheses, the heterotrophs, were now under very heavy pressure. Most of them must have become extinct. But some did survive by yet another adaptation. Some of the heterotrophs could very well have filled their requirements by incorporating other cells - possibly by cell fusion, a very common modern event - either by taking in their own kind, or by "ingesting" more abundant autotrophs flourishing because of their photosynthetic advantage. We shall return to these points soon after we consider other aspects of the oxygen revolution.

The new gas easily became a potent resource for the development of new metabolic initiatives, for exactly the same reason that organic molecules were unstable in its presence. A kind of new oxidation arrived on earth, one which made the extraction of energy from fuels many times more efficient.

The cells that developed the means to mount this new initiative would gain the upper hand as natural selection, operating as always to preserve and refine only the most efficient, soon elevated them above all the others.

THE ORIGIN OF EUKARYOTES

The ascent from the prokaryotes required even more advantages than those available from the recently won oxidative metabolism. At first, cells had to become larger, if just to escape the tyranny of the small forces generated everywhere (give me a very big ship to ride across the North Atlantic anytime), and to avoid being swallowed by others. But large size would have had other advantages. Larger volumes can accommodate greater internal complexity. That was really pivotal, because the next step forward demanded the compartmentalization of function and the division of labor. Specialized compartments take up space, and cells needed to increase in size if they were to accomodate those internal features.

Larger sizes require more energy to sustain their inceased volume. The new oxygen users certainly held that advantage since they were approaching maximum efficiency in energy extraction from available resources. But they still needed another very important ingredient if they were to successfully increase in *both* volume and complexity.

Larger volumes must be directed by proportionately larger amounts of DNA: increased complexity places additional stress on the nucleic acid content since there is not only more volume to instruct but also more to create. New genetic combinations were clearly required to accompany increased DNA content. Some cells, the presumptive ancestors of the archaebacteria, did appear to have the necessary genetic push. They were probably a line that had built into their DNA the powerful means to deliver new DNA combinations to their offspring. In addition, some of these cells could have transmitted relatively large quantities of DNA which they could have acquired by fusing with others, or by DNA replication which was not followed by cell divison. This is a situation that is commonly observed today, and it results in quantum jumps of doubling, sometimes quadrupling, DNA content per cell.

The cells with multiple copies of DNA would be at an advantage if they were to confine all their DNA within one special compartment which would also come to hold the enzymes needed for its replication and transcription. Once that happened, these cells made a major advance. They had nuclei, and so they are eukaryotes.21 They could also monitor their larger size and complexity. But they did not have the means to transform energy with oxygen or, for that matter, to fix it by photosynthesis. But that too would be cured.

Many scientists believe that the primordial eukaryote acquired photosynthesic capability and an oxidative metabolism in monumental acquisitions - that is, by the incorporation of prokaryotes with those capabilities. For reason unknown, digestion did not follow ingestion, and the prokaryotes continued to function inside their eukaryotic consumers providing them with the oxidative and photosynthetic advantages.

The advantages were mutual. The eukaryote was now equipped, through its prokaryotic internal guests, to transform energy by the most efficient means available: to perform photosynthesis, fix energy and make complex molecules; then to use oxygen to extract that energy. With sufficient energy from available resources, the host could reach larger sizes and exploit the potentials of its extra DNA. From the prokaryotic point of view, they were now inside where they were not only safer but also the occupants of a vehicle bound for higher levels of life. Because it was mutually advantageous, the union was symbiotic, and because it increased survival, the union lasted. The symbiosis persisted, and over the millennia, it became irrevocable. The prokaryotes became eternally fixed within the eukaryotes as their specialized compartments. The prokaryotic photosynthetic guests became the eukaryotic chloroplasts. The oxidative prokaryotes have evolved into the mitochondria. With such compartments and with their genetic versatility, the eukaryotes became the launching pads for all the higher forms of life.23

The rest is read in the statement that life has left in the universe. Once brought to the level of eukaryotes, the results were inevitable. Given the conditions, time, and little more, matter expressed its inexorable tendencies to live, to evolve, and to eventually explain how it all could have happened.

EPILOGUE

I have just shown that life arose in a series of "little bangs" that rumbled through the geological eras as a matter interacted with the conditions found on earth. At first the required molecules formed from simpler ones. Complexity increased as these molecules aggregated together, then segregated behind membranes,and developed a metabolism. Life itself began when a genetic mechanism was integrated within the metabolic framework, but made its greatest strides after the onset of photosynthesis and the appearance of free oxygen. This gas gave further impetus for the evolution of even more complexity. Under its umbrella the primordial cells acquired compartments and set the stage for the evolutionary leap into all the higher forms of life, including humans. And that is, essentially, the story of creation. If this were a modern creation myth, the hero would be matter, with time and circumstances as the other characters, evolution as the vehicle, and the mind as the prize.

The story reinforces and reaffirms humanist philosophy. No supernatural power need be involved to account for anyone's origin. And we have, of course, the argument that demolishes "scientific" creationism.

But more than that we have in our creation epic the basis for our relatedness. We are directly or indirectly related to all other organisms through common descent. But our relatedness does not stop there. We were made with the matter that also made the landscape. We are inextricably bound to it. We are in the landscape as much as it is in us.

The landscape is thus a metaphor and a model for existence. By nature the metaphor is paradoxical. Jagged mountains stand against flat plains. Wet and steamy, the tropics, flowing with life, stand below the ice locked crystalline arctic. The enormous forces let loose in earthquakes topple buildings, but serenity reigns in the pasture; and the eye, the one in hurricanes and the tornado, sits serenely,reined into the middle, by the fury outside. Then there is death that comes in the afternoon, birth in the morning, or is it the other way around.

The paradoxical metaphor mirrors the paradox we must live with. We cannot change it anymore than we can change the facts of mountains and earthquakes. But we can learn to understand them. We will be able to predict earthquakes, as we can now estimate the probability for tornadoes, to issue warnings, and to improve the chances of surviving catastrophes.

Perhaps one day we will also know imd understand the mind, our own, the terrorist's, the altruist's, and the ones that turn to religious fundamentalism, poetry, the exploitation of resources, and the trivia. By knowing these we can perhaps improve all of our lots.

And that will be the best we can ever do.

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I am indebted to Barry Lopez, an extraordinary naturalist and author of uncommon power and conscience. His *Artic Dreams* (New York, 1986), inspired me to give this essay its present form.

ADDENDUM

Estimates about the composition of the primordial atmosphere have been changing and a new consensus is rapidly forming. After more than thirty years, opinons have shifted to an atmosphere consisting mainly of carbon dioxide and nitrogen rather than the methane, ammonia, and hydrogen outlined above. Other features remain the same: both carry water vapor but neither contains free oxygen.Both also yield essentially the same products after the Miller-Urey synthesis but they do not produce them in the same amounts. The newer combination yields smaller quanities (see Robert Shapiro, *Origins. A Skeptics Guide to the Origin of Life*, New York, 1986, pp 98-116).

NOTES

I. Edward O. Wilson, *Human Nature* (Cambridge,Mass., 1978),206.

2. Ibid., 207.

3. Jeremy Rifkin is a vigorous champion of "species rights." He argues passionately against any technological tinkering with genes. Many scientists agree that care is essential in such matters, and share some of Rifkin's concerns. His tactics, however, create problems. They are considered somewhat devious at their best (see Stephen Jay Gould's Viewpoint, "On the Origin of Specious Species," *Discover.* [JAN 1985], But stronger views are also on record: "Rifkin Against the World," *Los Angeles Times.* (17 April 1986) reprinted in *Science,* 233 (1986), 704. *Science* reprinted another editorial alongside "Rifkin Against the World." That one is entitled, "A Novel Strain of Recklesness," *The New York Times,* (6 April 1986). This article concerns commerce in genes, and the regulatory agencies. Both editorials placed side by side frame the Rifkin paradox. His tactics become the center of controversy. But the real issue goes deeper. It is the ethics of biotechnology, not the hollow Rifkin rhetoric, that require the scrutiny and attention of an informed media and populace.

4. The Latin for, "God Wills!"

5. Experiments are not the only vehicle to test scientific validity. Darwin did not perform any experiments to derive the theory of evolution. The data upon which we based the theory of evolution, as it was presented in Darwin's *Origin of Species,* were drawn from congruence with the context of the historical facts which he amassed. Stephen Jay Gould gives an excellent account of historical science in his "Evolution and the Triumph of Homology," *American Scientist,* 74 (1986),60-69.

6. For some further reading on this subject I recommend S. E. Luria's *Life - The Unfinished Experiment* (New York, 1973).

7. See Sherri L. DeFauw, "Evolution: The Highlights," *Humanism Today,* 3 (1987), 39-46, for an excellent review of evolution and natural selection.

8. The splitting off of a third form of life is a relatively recent and important development. A more complete picture of the methodology and the evidence behind this new split can be found in: Carl R. Woese, "Archae bacteria," *Scientific American,* 244 (1981), 98-122.

9. According to Woese *(ibid.,* 122) the eukaryotic gene for the ribosomal A protein was appropriated from the Archaebacteria.

10. The names of Watson and Crick will always be remembered for their extraordinary contribution in the elucidation of the three-dimensional structure of DNA and the role of complementary base pairing, and rightly

so. However, we should be aware that there were others who were involved in the DNA revolution. Their contributions were less dazzling than the Double Helix, (James D. Watson, *The Double Helix* (New York, 1968), but they were, nonetheless, important. So as a lesson in the sociology of science, and in recognition of their efforts, I recommend the following readings: Frankin H. Portugal and Jack S. Cohen, *A Century of DNA*, (Cambridge, Mass, 1977); Maclyn McCarty, *The Transforming Principle*, (New York, 1985); A. Sayre, *Rosalind Franklin and DNA* (New York, 1975).

11. A. G. Cairnes-Smith, "The First Organisms," *Scientific American*, 252 (1985), 90-100. This is a very well written and thought provoking article.

12. Freeman Dyson, *The Origins of Life*, (New York, 1985). Here is a clearly written exposition by a famous physicist.

13. Francis Crick, *Life Itself Its Origin and Nature*, (New York, 1982). An interesting treatment given by one of the codiscoverers of the double helix.

14. An element is defined as a substance that cannot be broken into simpler parts by ordinary means. But the elements can become much more: Primo Levi, *The Periodic Table*, (New York, 1984).

15. Stanley L. Miller, "A Production of Amino Acids under Possible Primitive Earth Conditions," *Science*, 117, (1953), 528-530. If anyone wants to set this experiment up in their basement, see: C. L. Strong, "The Amateur Scientist: Experiments in Generating the Constituents of Living matter from Inorganic Substances:" in *Life: Origin and Evolution.* ed. Clair Edwin Folsome (San Francisco, 1970), 57.

16. C.L. Strong, *ibid.*. Also, S.W. Fox and K Dose, *Molecular Evolution and the Origin of Life.* (New York, 1977), for a more authoritive review of the earlier work.

17. Barry F. Madore and Wendy L. Freedman, "Self-organizing Structures," *American Scientist*, 75 (1987), 252-259. This paper shows how propagating patterns order can rise from chaos by spontaneous processes.

18. The Soviet Biologist, Alexandr Ivanovich Oparin, the founder of modern scientific inquiry into the origin of life, introduced coacervates. His book, *The Origin of Life*, (New York, 1953) is probably the classic in the field. For another treatment, which reviews some of the modern developments in context of metabolism and chemical evolution, can be found in: Richard E. Dickerson, "Chemical Evolution and the Origin of Life," *Scientific American*, 238, (1978), 70-86.

19. Manfred Eigen, William Gardner, Peter Schuster and Ruthild Winkler-Oswatisch, "The Origin of Genetic Information," *Scientific American*, 244 (1981), 88-118.

20. The traditional views held that primitive bacteria of the genus *Clostridium* (the group that produces the deadly gangrene, botulism, and tetanus) were the closest representative of the primal cells. However, the discovery of the archaebacteria seems to be changing this. Other possibilities from among this group now appear to be likely alternatives. Another traditional view was that the earliest cells were most probably heterotrophs. The *Clostridium* are heterotrophs, but the archaebacteria are autotrophs. Autotrophy does not necessarily mean that it was easy to meet nutritional requirements. The autotrophs would be as severly stressed during the primordial energy crisis. They require electrons, and the resources for electrons can become just as scarce as the more complex molecules required by heterotrophs.

21. The nucleus is one of the primary diagnostic features for the eukaryotic (which means true nucleus) level of organization. However, many scientists believe that eukaryotes began with the acquisition of mitochondria. This is a mistake. Eukaryotes began when the nucleus evolved; the mitochondria, apparantly, came in later (T. Cavalier-Smith, "Eukaryotes with no mitochondria," *Nature,226* [1987], 332).

Molecular evolutionists (they attempt to establish relatedness through homologies in nucleotide sequences) are now proposing that the first eukaryotes were something like the extant archaebacterium, *Thermo-plasma A cidophilum* (see Dennis G. Searcy, Diana B. Stein and George R. Green, "Phylogenic Affinities Between Eukaryotic Cells and a Thermophilic Mycoplasma," *Biosystems,* IO [1978], 19-28.) After developing a nucleus, such an organism is believed to have evolved into a form related to the protozoan *Giardia,* that is not a common cause of dysentery (T.Cavalier-Smith, *Ibid.).*

22. The hypothesis that chloroplasts and mitochondria (and, perhaps, other organelles) were once free living prokaryotes is known as the endosymbiotic hypothesis. Lynn Margulis was instrumental in bringing the endosymbiotic theory forward again after its initial decline in the early 1900's (see Lynn Margulis, "Symbiosis and Evolution," [1971] reprinted in *Life: Origin and Evolution,* ed. Clair Edwin Folsom [San Francisco, 1979], IOI-l IO for some essential features of her hypotheses. She also authored the very readable *Early Life,* (Boston, 1982), in which the ecology of microbes and their evolution are clearly explained. One of the most recent books, with Dorian Sagan, *Origins of Sex* (New Haven, 1986), gives the updated version of her view of endosymbiotic hypothesis. Perhaps less to the point these authors also revived an earlier hypothesis on the origin of sex, one that is different, and one that could very well spark a new wave of research.

The endosymbiotic theory has recently been reviewed (Michael W. Gray and W. Ford Doolittle, "Has the Endosymbiont Hypothesis Been Proven?," *Microbiological Reviews*, 46 [1982],1-42) from the point of view of molecular biology. Has it been proven? The authors believe that the evidence is strongest for chloroplasts.

Some recent research on the nature of the primordial eukaryotic host should be of some interest. There is evidence that *Giardia* (see note above) could well be the remnant of the primordial hosts of the oxidative prokaryotic symbionts that went on to evolve into mitochondria, although other alternative organisms have been proposed (c. R. Vossbrinck; J. V. Maddox, S. Freedman, B. A. Debrunner-Vossbrinck and C. R. Woese, "Ribosomal RNA Sequence Suggests Microsporidia Are Extremely Ancient Eukaryotes," *Nature,* 326 [1987], 411-414).

23. For a couple of essays which expand upon the human implications of endosymbiotic theory, see Lewis Thomas, "Organelles as Organisms," *The Lives of a Cell,* (New York, 1974), 69-74, and "Some Biomythology," in the same book, (121-126).

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