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DARWINIAN LIFE

From so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved.

—Charles Darwin, *On the Origin of Species*, 1859

In the summer of 2007 I entered into a new experience: teaching the science of evolution to entering university students. Each of the nineteen students in my class, none older than eighteen years of age, started his or her first university class with some mixture of optimism and trepidation. Most, it turned out, wanted to be scientists. Yet in a series of short papers, most also readily admitted that while they had been well prepared in their high school classes in various mixtures of mathematics, chemistry, physics, and biology, virtually none had learned anything about what is variously labeled as evolutionary theory or, if one has a more creationist bent, Darwinism.

The reason for this omission was easily ascertained. Most high school teachers have stressful enough lives dealing with the daily traumas of teaching in U.S. high schools—why add extra drama by entering into one of the most emotionally charged of all subjects, evolution? Many a teacher has had the very unpleasant experience of describing theories about human phylogeny and meeting an angry, fundamentalist parent soon thereafter. So the subject is largely ignored.

Unfortunately, when evolution is ignored, other allied sciences are ignored as well. Perhaps the most important of these deals with the origin of life. For reasons also obscure, one of the most perplexing and important of scientific questions—how life first appeared on Earth—is ignored in basic university biology courses and, if mentioned at all, is discussed in brief detail in a more advanced evolution course. But this seems curious, for how life first appeared and how it later evolved the ability to evolve were different processes. (As we shall see, the ability to evolve became an inherent property of Earth life, but surely only after the synthesis of life's building blocks.) The current modes of evolution involving genes on DNA, itself massed together in a chromosome, were a long way in the future when various snippets of amino acids were assembling into some proto-RNA molecule. Yet how life first came into existence is a viable field of study, and for want of any better place this topic is usually dealt with in an evolution class.

Thus, on my second day in class, I asked the assembled multitude to write me a short essay on the definition of life. The results were all over the map. While some honed in on chemical definitions, the majority leapt toward the metaphysical, imbuing life with a vast array of mystical properties, ranging from the minimal to truly godlike. What came through, however, was a fundamental property that does not usually make it into the textbooks but is at the heart of the arguments here: that life in the aggregate acts very differently from life as an individual. However, those imbuing life with properties over and above those of an individual saw those properties as inherently "good" and helpful to other life—with the sole exception of we humans, which were viewed rather guiltily as not following life's lead in making things better. I agree with my students' prescient sense that life as a whole acts differently from life as an individual. Where I disagree is about the ultimate effect of life on itself.

An analogy about this disconnect can be seen in the relationship between individual humans and the human race. Each of us lives our life, usually hoping for, and living in ways to create, as much happiness as possible. Many of us work diligently to reduce the environmental "footprint" of our existence. Yet in aggregate we are clearly changing the physical Earth, and changing conditions for both ourselves and other life. So too with "life": as an aggregate it has major effects on itself as well as the planet. This aspect of life might certainly help explain some of the behaviors proposed at the heart of my arguments here.

Let us begin this argument with the most minimal definition of life, followed by a definition of Earth life, for it is one of life's inherent properties that is the heart of the problem.

The question "What is life?" is deceptively simple, with no simple answer. Perhaps the most parsimonious answer is as follows: "All life forms are composed of molecules that are not themselves alive." This definition, as imprecise as it is, does hint at a deeper truth. At what level of organization does life "kick in"; in what ways do living and nonliving matter differ? Most who have thought deeply about what life could be, and what chemical forms it could take (Ward 2005), *believe* that Earth life is but one kind of possible life. But no one on this Earth can prove that there is any life beyond that of the Earth, and indeed one of the astonishments about life on Earth is not how diverse it is (which of course it is, at least at the level of species), but how *poor* the Earth is in the kinds of life. While those who worry about biodiversity rightly point out how the Earth is losing species, the reality is that there is only one kind of life on Earth—our familiar DNA/RNA life. E. O. Wilson's magnificent 1994 book, *The Diversity of Life*, could in reality be retitled *One*.

But what are the characteristics of life, and then Earth life, and why are these central to the arguments here? I will argue that one of the attributes that most experts equate with being "alive" is the ability for the entity to evolve in a way that would have been familiar to Charles Darwin, an evolution that now bears his name: Darwinian evolution. It is that aspect of Earth life (and perhaps all life, since the very number of stars in the cosmos make the presence of life beyond Earth as close to a certainty without being one as there could probably be) that, to many, is the source of Earth life's singular success. And yet how important is the behavior of an individual compared to the behavior—or, perhaps more properly, the effects—of the collective? My thesis is that the inherent property to evolve is also the source of the inherent "suicidalness" of life—a facet of what I will define as the *Medea principle,* to be posed and referred to here as a hypothesis.

Perhaps a better question than "What is life?" is "What does life do?" Physicist Paul Davies, who has pondered the "What is life?" question more than virtually any other thinker, listed the following:

Life metabolizes. All organisms process chemicals and in so doing bring energy into their bodies. But of what use is this energy? The processing and liberation of energy by an organism is what we call metabolism, and that is necessary to maintain internal order.

Life has complexity and organization. There is no really simple life, composed of but a handful of (or even a few million) atoms. All life is composed of a great number of atoms arranged in intricate ways. But complexity is not enough; it is organization of this complexity that is a hallmark of life. Complexity is not a machine. It is a property. It is also something the life "does."

Life reproduces. This one is obvious, and one could argue that a series of machines could be programmed to reproduce, but Davies makes the point that life must not only make a copy of itself, but also make a copy of the mechanism that allows further copying; as Davies puts it, life must include a copy of the replication apparatus too. Again, there are machines that allow life to copy itself, but the process is not that of a machine.

Life develops. Once a copy is made, life continues to change; this can be called development. Again, this is a process mediated by the machines of life, but also involving processes that are quite un-machinelike. Machines do not grow, nor change in shape and even in function with that growth.

Life is autonomous. This one might be the toughest to define, yet it is central to being alive. An organism is autonomous, or has self-determination. But how "autonomy" is derived from the many parts and workings of an organism is still a mystery, according to Davies. Yet it is that autonomy that again separates life from machine.

Finally, Davies noted: *life evolves*. According to Davies, this is one of the most fundamental properties of life, and one that

> is integral to its existence. Davies describes this characteristic as the paradox of permanence and change. Genes must replicate, and if they cannot do so with great regularity, the organism will die. Yet, on the other hand, if the replication is perfect, there will be no variability, no way that evolution through natural selection can take place. Evolution is the key to adaptation, and without adaptation there can be no life. Again, a process, not a machine.

Davies is far from alone in advocating that Darwinian evolution is a fundamental property of life, nor was he the first to do so. A decade before Davies so eloquently made these observations about life, the great Carl Sagan famously wrestled with the question of what life is. Unlike most others thinking about this topic, who were dealing only with life as it is found on Earth, Sagan came at the problem with a specific goal: he was interested in life beyond Earth, and at the time of his observations about life, in the mid-1970s, he was involved in several NASA missions involved in searching for such life, most famously the Viking missions to Mars. Sagan's definition of life, which was largely taken up by NASA and is still used to this day, sees life as *a chemical system capable of Darwinian evolution*, meaning that there are more individuals present in the environment than there is energy available, so some will die. Those who survive do so because they carry advantageous heritable traits that they pass on to their descendents, thus lending the offspring greater ability to survive.

The view that evolution is an inherent property of life has come to be called the evolutionist view. For instance, life has been defined as being a self-sustained chemical system capable of undergoing Darwinian evolution, as well as a self-replicating, evolving system based on organic chemistry, as well as a system capable of evolution by natural selection. Finally, life has been called a material system that undergoes Darwinian evolution.

So just what is "Darwinian evolution"? We should briefly describe its basic tenets before going any further. While Darwin is credited with a "theory of evolution," in fact he proposed two separate and testable hypotheses. The first is that all life on Earth came from a single common ancestor. Second, he proposed a principle of variation: that life reproduces to produce slightly different variants of the parent (as well as progeny that closely match the parent, or, in reproduction through cloning, forms that are genetically similar). But Darwin also noted that most "parents" produce more offspring than can live because of shortages of food, or shelter, or other necessities of life. Because of a surplus of offspring, in most instances some will perish. Those that survived did so in the long run—and indeed we are talking of many generations—because they had characteristics that made them in some way superior to others of their own species. These characteristics, such as larger size, which is a very common trend in evolutionary lineages, must also be "heritable"—that is, the characteristics have to be passed on to the next generation.

Darwin saw this competition as "survival of the fittest," and he gave the process the technical name "natural selection." Over the long run, the survivors would be those with characteristics (hereditable characteristics, that is, ones that can be passed on to the next generation and not just ones acquired during the life of the individual, such as a human sex change operation) lending the greatest "fitness," or ability to survive. Examples are many, such as the few giraffes with ten-foot-long necks among a herd with seven-foot necks in places where the lowest vegetation is nine feet above the ground; the fastest-swimming fish in a lake where the predators can catch the slowest and even median-velocity swimmers. These survivors then pass on these successful characters to their offspring, and evolution has taken place.

Speciation, the formation of an entirely new species, is a larger-scale process. A species is deemed separate if it can no longer interbreed with its parent's populations. For new species to form, most commonly there must be geographic isolation of a subset of a smaller population into a new environment cut off from the larger population, one that has different challenges for survival. Over some generations these new environmental challenges would cause evolution of forms dissimilar enough that if the two populations should again come into contact, the two gene pools are now so different that breeding does not produce successful offspring.

Thinkers on the subject have come to agree that Darwinian evolution is certainly a key property of Earth life, or RNA/DNA life, and perhaps it is a necessary property of all life in the Cosmos.

DEFINING EARTH LIFE

With all the apparent diversity of life on Earth, all Earth life yet discovered shows a unifying characteristic—it all contains DNA. This is why I suggest that the true diversity of life on Earth is 1.

Composed of two backbones (the famous "double helix" described by its discoverers, James Watson and Francis Crick), DNA is the information storage system of life itself—the "software" that runs all of Earth life's hardware. These two spirals are bound together by a series of projections, like steps on a ladder, made up of the distinctive DNA "bases," or base pairs: adenine, cytosine, guanine, and thymine. The term "base pair" comes from the fact that the bases always join up: cytosine always pairs with guanine, and thymine always joins with adenine. The order of base pairs supplies the language of life: these are the genes that code for all information about a particular life form.

If DNA is the information carrier, a single-stranded variant called RNA is its slave, a molecule that translates information into action—or in life's case, into the actual production of proteins. RNA molecules are similar to DNA in having a helix and bases. But they differ in usually (but not always) having but a single strand, or helix, rather than the double helix of DNA. Also, RNA has one different base from DNA.

RNA is tantalizing stuff. While indeed it is "hardware" in carrying amino acids to protein-building sites in the ribosomes, it is clear that some RNA has multiple functions, including information storage. There is an apparently important regulatory role played in eukaryotes by nonprotein-coding RNA, which is an example of RNA acting simultaneously as software and hardware.

DNA provided the answers to many of the mysteries of genetics, answering the question, once and for all, about what is a gene, for the nature of inheritance, from Darwin's time to the twentieth century, had remained a most vexing question. James Watson and Francis Crick made the great discovery—one that launched an enormous revolution in biology—and their great discovery was announced in a paper in the journal *Nature* that was but a single page long. Their finding was actually a model, not an experimental result, but the model had enormous predictive power. It became clear that a gene is made of DNA, and that one gene makes one protein. Watson and Crick proposed that one half of the DNA ladder serves as a template for re-creating the other half during replication. Each gene is a discrete sequence of DNA nucleotides, with each "word" in the genetic code being three letters long.

How does a gene specify the production of an enzyme? It was Francis Crick who suggested that the sequence of bases was a code—the so-called Genetic Code—that somehow provided information for the formation of proteins, one amino acid at a time. The information coded had to be read (transcribed) and then translated into proteins. That is where RNA comes in. Earth life uses twenty amino acids. Not nineteen. Not twenty-one. *And always the same twenty!* DNA codes for RNA, which codes for proteins, which are all made up of combinations of the twenty amino acids. This, then, the central dogma of molecular biology, may also be called a central characteristic of Earth life.

HOW EVOLUTION ARISES

Genes are the blueprints necessary to make Earth life's major structural and chemical partner: proteins. Proteins perform the various functions of the cell. A protein's action is determined both by its chemical constituents and by its shape. Proteins become folded in highly complicated topographies, and often their final three dimensions shape their actions.

So how does DNA specify a particular protein? A typical protein might be made up of 100 to more than 500 individual amino acids (but all of those same twenty kinds), and thus its gene, the sequence of nucleotides coding for the protein on the DNA strand (since the string of amino acids that make up the protein are coded on the DNA strand), will be composed of 300 to 1,500 or more sets of "steps" on the DNA ladder. These are arranged in linear order along the DNA strand, like letters in a sentence. And, like a sentence, there will be spaces and punctuation as well (like *stop!*). The RNA slaves grab these and take them to a ribosome, where the actual protein is constructed.

This information flow mainly goes one way only—from DNA to RNA (though, as noted above, some RNA has no role in protein formation but functions as a regulatory molecule). The poor RNAs have no say in any of this: go here; build that, bossed forever from above by DNA. All the proteins being built by the ribosomes, at the direction of the RNAs (themselves slaves to the DNA), do one of two things: they build a structure, or, more commonly, they function as enzymes that catalyze a chemical reaction in the cell itself important for maintaining life function—such as metabolism.

Having a DNA is obviously not all there is to life. We need a wall (membrane) to enclose our cell, and a solvent to fill it with. Both the wall or membrane structure and the solvent are also features that we can use to identify common Earth life. The biochemist Steven Benner also suggests that a requirement of life is some sort of scaffolding, for both building blocks of our life structure and to hold biomolecules in correct orientation so as to allow chemical processes of life. Our Earth life uses carbon as the scaffolding element, but silicon could be used as well if there are side branches on long chain carbons on which silicon compounds could bond.

So much for the structure and building of life. Where does evolution come in? Life seems to be composed of three separate sets of "machines"—one for extracting energy from the environment, one for building and maintaining the physical body of the particular life form, and one for maintaining—and then replicating—the information and blueprints not only for the two sets above, but for itself as well. Evolution takes place because of actions by the information system. In fact, it is the very complexity of the information system that allows and sometimes inadvertently prods evolutionary change.

Replication is by far the most difficult process required by life, more so than either building structures or extracting energy from the external environment. DNA and RNA are extremely complex molecules and are necessarily large, even in the simplest of organisms. It now seems that about 200 separate genes are needed for the simplest Earth life. This is compared to about 15,000–25,000 genes in humans, and even more in some other animals and plants. This is far too many genes to put on a single strand of DNA, so life has resorted to multiple strands (chromosomes), each of which has to be replicated.

Highly important to evolution are changes to the genome caused by mutations. This causes a code change, and it can occur either on the chromosome itself during nonreplication times or during replication as a result of any number of replication mistakes. Most such changes are deleterious, causing more harm than good. But they really can change the nature of a gene pool when a change increases fitness of an individual.

Finally, to really bring about variability, sexual reproduction cannot be beaten. It is no wonder that the largest evolutionary rates, and the appearance of so many evolutionary novelties, postdated the evolution of sex.

It is thus the very complexity of life that leads to the mistakes—few enough, but over the long roll of time quite sufficient to continuously reshuffle the deck of genes of any species.

Life seems to have appeared on this planet somewhere between 4.1 and 3.7 billion years ago, somewhere near the end of the Hadean era, or early in the Archean era—or some 0.5 to 0.7 billion years after the Earth originated. Perhaps it is older still, going all the way back to 4.4 billion, the time when liquid water may first have appeared on Earth. However, this is a window of time early in the Earth's history when no fossils were preserved, thus obscuring our understanding of life's earliest incarnation. The oldest fossils that we do find on the planet may be from rocks about 3.6 million years of age, and they look identical to bacteria still on Earth today. (But there is still a debate whether these are indeed fossils of life, or inorganic precipitation of limestones that look like later, layered life). There may have been earlier types of life not now represented on Earth, but our present knowledge suggests that simple oval or spherical bacteria-like forms were the first to fossilize and may have been the shape of the first life on Earth as well. By the time that these appear in the fossil record, we can be sure that evolution was well under way.

COULD THERE BE NON-EARTH LIFE, AND WOULD IT NECESSARILY BE NON-DARWINIAN LIFE?

It now seems reasonable to assert that all known Earth life is Darwinian. Would it be possible for there to be "non-Darwinian" life—life that does not evolve? It is possible to imagine alternative biochemistries of life. Let us take a brief diversion from the themes of this book to see the possibilities. These can be broken down as follows:

1. *Life using different amino acids*. One of the most compelling observations supporting the notion that all life on Earth is descended from a common ancestor is the planetwide use of the same twenty amino acids as the components of encoded proteins. This biochemical uniformity is not obviously demanded by prebiotic chemistry.

2. *Life with chemically different DNA.* An analogous conclusion for terran genetic matter is now possible based on many experiments in synthetic biology. As with alternative amino acids, it appears that DNA molecules using a different "code" not only can work but also can reproduced. For example, an artificial genetic system synthesized in labs at the University of Florida has sustained up to twenty generations of replication (Sismour and Benner 2005). They can even be copied with mutations, where the mutations are themselves replicable. Thus these synthetic genetic molecules are artificial Darwinian chemical systems, according to the research group in Florida headed by biochemist Steven Benner.

3. *Life with a different solvent.* General experience in chemistry suggests that metabolism can operate efficiently only when metabolites are dissolved. Water is an excellent solvent, by many measures. But many compounds are not soluble in water, and indeed there may be habitats elsewhere in the solar system where solvents remaining liquid at either higher or lower temperatures than the 0–100°C range of water would be necessary for any life to exist there. Several of these are shown in figure 1.1, with their temperature ranges.

While the various life forms described above would all have to be classified as "aliens," in one way they all are similar to Earth life: all

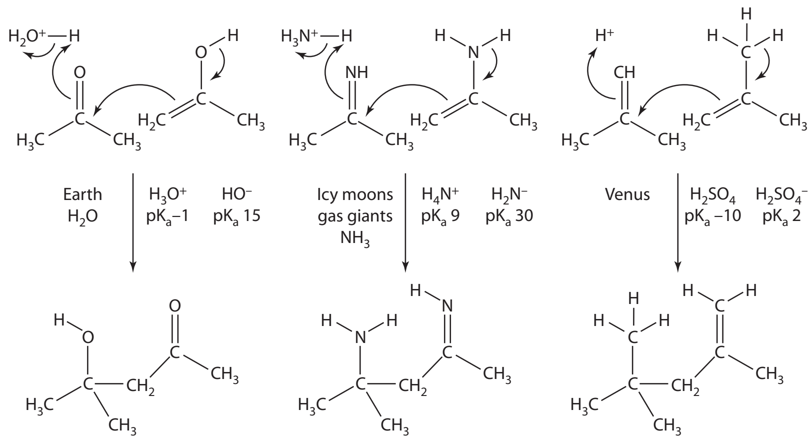

Figure 1.1. Different solvents would favor different, although analogous, chemical reactions to support metabolisms in life residing in different points relative to the star in a solar system. Here are shown three analogous mechanisms for forming carbon-carbon bonds, where the desired reactivity is conferred upon the reacting species by a C=O unit (favored in water), a C=N unit (favored in ammonia), or a C=C unit (favored in strongly acidic solvents such as sulfuric acid). Source: Benner et al. (2004).

should be able to evolve (or there is no chemical reason that they could not). But is there any way there can be nonevolutionary life? In 2003 and 2004 a United States National Academy of Science panel looked at potential chemistry and metabolism of aliens, using the various forms described above as potential candidates. But when they also explored what could be even more alien varieties of what they euphemistically called "Weird," the group concluded that none might be so weird as a potential life form that does not include Darwinian evolution in its makeup. The panel felt that non-Darwinian life is on the other side of the divide between weird (the varieties listed above) and what they called the "truly weird." That line also demarcates the "possible" from the "improbable."

Let us assume that there is non-Darwinian life. Life that does not evolve might be necessarily short-lived or perhaps inhabit environments that are so unchanging as to render the need for evolution moot. Oddly enough, it is probable that the earliest Earth forerunners of life were unable to evolve. There may have been spheres of cell wall with primitive metabolic systems that lacked genomes. They came together, operated in a manner that extracted energy from the environment, perhaps even showed a primitive kind of replication, and then died. Perhaps even primitive genomes would allow replication, and more than a single generation would live. Eventually, however, the lack of evolutionary response would cause death. It is when evolution kicked in that life became life as we know it. And with that property, life altered its effect on the physical world, and then on itself.

It seems likely, then, that most life that can be imagined is characterized by Darwinian evolution. The many varieties listed above certainly suggest that while we may find locales in space where terran life could not survive, we may indeed find exotic kinds of life. Yet, if it is Darwinian, and we have fled our Earth to get away from this trait, it may be that everywhere we went, we would find the same problems. We can assume that any planet with Darwinian life will be hazardous to our health.