Life as We Do Not Know It

The NASA search for
(and synthesis of) alien life

Peter D. Ward

PENGUIN BOOKS

For Don Brownlee, Joseph Kirschvink, Geoff Garrison, Ken Williford,
Jim Haggart, Ken MacLeod, and Roger Smith: Colleagues

And Patrick, Nicholas, and Christine,
of course

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Preface

There are four goals that I am trying to accomplish in the following pages.

The first is to bring the public up to date on progress in the relatively new scientific field called astrobiology, the study of life in the universe, which of course includes the study of life on Earth. An astonishing rush of twenty-first-century discovery has rendered obsolete most books on this subject, even those published in the last five years. Some of the new knowledge that has made so many excellent titles so out-of-date has been accumulated by space probes, and some by scientists feverishly working here on Earth. The sum of these robotic and human efforts has given us a new and much more positive view of prospects for life beyond Earth in our solar system, as well as a wealth of new insight into how earth life arose and what it is. In pages to come I will show why there is such new optimism about life beyond Earth, and optimism as well about a once seemingly impossible task, the synthesis of artificial life here on Earth. Yet as wonderful as this story of new discovery is, by itself it would not have been enough to tempt me away from other research projects just to write such a book. However, without this updating I could not coherently accomplish my other, more interesting goals, all of which deal with presenting new ideas and research that I either am involved with or help fund through a large NASA grant that I administer.

Chapter 1

What Is Life?

From a commonsense viewpoint, nothing seems easier than to tell what is alive and what is not.

—Gerald Feinberg and Robert Shapiro, *Life Beyond Earth*

The small submarine headed down toward the blackness of the deep sea bottom, thousands of feet below, and the cramped men inside could only wait out the seemingly endless descent, passing the time by peering through the *Alvin*'s thick glass portholes. The voyage began in the sunlit portions of a sea filled with life modern in aspect but then descended back through the ages, for the deep sea is the home of many living fossils, species of great antiquity. Finally the voyage landed at the site where life may first have started, a place that might still harbor microbes that were present when DNA life first arose. Such a place might harbor other life as well, the predecessors of our familiar DNA life. But at what point as we go back do we reach the transition from life to nonlife? That particular question was about to become even more problematical on this day in 1978.

At first, the rich fauna of the daylit upper reaches of the subtropical Pacific surrounded the submarine: clouds of plankton, most evolved from the Cretaceous period on; schooling small fish and the larger piscine predators that pursued them, relicts too of the

Cretaceous period; umbrellas of jellyfish and their ilk, from vastly older stocks, but made up of species that might be very recently evolved; the shooting forms of arrowworms; the darting and resting of crustaceans that seem even more modern than the fish in these sunlit seas. Farther downward the submarine descended, and the brightness and color of the sea changed, a gradual journey through the spectrum of blue in all its shades toward ever-deeper hues. Now life was less noticeable and different in aspect. The sardine shape of the fish changed, as did the look of the invertebrates, and now, at least to a paleontologist, the world looked more Mesozoic than otherwise. An occasional squid appeared, and even these no longer looked like their familiar surface-dwelling cousins. Long tentacles draped from the head regions in some, while others had squat, ammonia-filled bodies resembling tiny hot-air balloons. These exotic squid were probably the closest living relatives in both ancestry and ecology to the vast race of the extinct ammonites, poor victims of the end-Cretaceous asteroid, and they themselves were of great age. Here in the mid-water now, in a place as far from the bottom as from the top of the sea, there lived a fauna that depended on flotation sacs to keep it permanently suspended—a fauna from antiquity. Through the windows of the small sub, deeper now, more than a mile beneath the surface, the scientists could see undulating floaters, or slowly swimming invertebrates giving off rainbows of shimmering color. Deeper still, approaching two miles deep, small lights, like drifting stars, amid the surrounding pastures of life, not unlike fireflies at dusk on a warm Ohio evening, began to appear in the darkness. The larger carnivores—the peculiar fish and squid of these great depths—some amazingly grotesque with huge mouths lined with sharp teeth, on occasion passed by the windows. All were countershaded, with light-lit bellies and dark upper surfaces, so that anything above them would see only black, and anything below would not notice their silhouettes against the faint light of the far-distant surface. All had a shape that comes to us from the distant Paleozoic, when the platy placoderms and armored arthrodires known from spectacular fossils recovered in the Cleveland shale or Old Red Sandstone evolved the peculiar heterocercal or reversed shark-shaped tails that are found only on these deep-living species and on the fossils from the four-hundred-million-year-old seas of ancient planet Earth.

As the deep blue of the tropical sea lost finally all color and was replaced by velvet night, the great searchlights of the *Alvin* switched on, bringing bright light to a region that had been unlit for millions of years, and the sub finally reached the bottom, a journey down, and one seemingly back in time, to the dawn of life on Earth. An hour had passed since the submergence. After the seemingly endless descent, when the men's imaginations had already cataloged the many ways that the submarine could fail its fragile inhabitants in the pressurized and cold depths, the bottom was finally spotted. Stark, lifeless, it resembled all the sea bottoms from the time before the Cambrian explosion, that moment 550 million years ago when the animal phyla sprang into existence. For 3.5 billion years prior to that moment all sea bottoms had been barren of any life but microbes, barren like this one.

For a time the *Alvin* glided over this desert sea bottom, a vision, perhaps, of what the deep-sea bottom of Europa might look like, surely also a smooth expanse of sediment in absolute darkness, but is it, or even this sea bottom, really lifeless? Then, shockingly, the smooth mud of this deep Pacific Ocean bottom gave way to a lithic landscape. A tangled rocky wilderness, the land of the submarine volcanic vents, lay illuminated below the *Alvin*. The bottom was like a disordered junkyard, with vast fields of pillow lava and twisted toothpaste squeezes of now-solid rock covered with a patina of sediment. The *Alvin* was about fifteen feet above the bottom now as it powered over the endless fields of volcanic rock, when its startled humans found themselves among a sudden profusion of animal life, one unlike that of the surface regions. It was a vent fauna, the strange animal fauna that had first been seen only two years before during dives in the Galápagos Islands. But those dives had been on a bottom far more peaceful than this one. This water became hazier, filled with dustlike particles and larger flocculation of repulsive-looking slime. Now there were tube worms, and white clams and crabs, and catalogs of other invertebrates unknown to humanity. In the worms and crabs and clams there was no doubt that the *Alvin* had found life—weird life, of course, but unambiguous vessels of earth life. But what of the floating slime, the white snowflakes that clouded what had been a pristine sea only minutes before? What was this material? Was this life?

The rocky bottom became more dissected, with walls and deep, narrow canyons appearing. The rocks in this new canyon land were covered with brown growth—mats of microbes?—and while the occupants of the small sub could not know it, much of the microbial slime that they viewed amid this deep rocky rubble was, like the larger animals, composed of living fossils, but in this case, species not of some Paleozoic age but of a far more ancient time, the time of the earth's youth, time measured in billions, not millions, of years. Suddenly and unexpectedly a tall spire of rock appeared dead ahead. It was covered with life, but the scientists looked at something far more arresting: This vertical rock column was belching shimmering black smoke into the dark water at a prodigious rate. Beyond, in the murky water, other tall chimneys could be dimly seen. Some were three or four stories tall. There was animal life here, most notably large white clams and spectacular tube worms, forms that had been seen on the *Alvin*'s dives off the Galápagos Islands, but it was not the animals that so startled the astonished scientists in the small submarine. The submarine had seemingly entered a Tim Burton nightmare, the Gotham version of Industrial Revolution England, in which tall black chimneys of rock spewed blacker smoke into the clear seawater over a dingy dark town of jumbled rocky tenements. The scientists had reached the industrial heart of the planet. Humans, for the first time, were seeing a landscape of the black smokers, and a whole new vision of how life first formed on Earth, and perhaps anywhere else, was conceived.

The black smokers had to be more closely investigated. The cramped scientists aboard the *Alvin* had the pilot use the vessel's mechanical arm to knock off the top of one of the rocky smokestacks, and in response the decapitated chimney belched its noxious

black liquid at an even faster rate. Temperature probes were cautiously inserted near the beheaded smoker. The black smoke (actually a superheated fluid coming from deep within the earth rather than real smoke) was found to be hot—nearly 100°F in temperature, in fact. This was far hotter than the hottest temperature recorded in the first of the deep-sea vents found in the Galápagos Islands two years prior to this dive off Mexico, which had been about 60°F. The scientists suspected that the temperature gauge was somehow giving false readings. But repeated analyses showed that the hot temperatures were real. How hot was the fluid before it left these tall lithic chimneys?

Later, when the *Alvin* was back on its mother ship and the maintenance crew could work on its instrument package, the temperature probe was examined. Its plastic end was melted. The excited scientists did a quick experiment to find the melting temperature of the tough plastic. It was found to be over 350°F, well in excess of the 212°F temperature at which water boils. Superheated water was apparently emanating from these strange geological chimneys, the black smokers. Better thermometers were quickly built onto the *Alvin* probe system. On subsequent dives the researchers could only read their temperature data with heads shaking in astonishment. The temperature of the black fluid coming from within the smokers was measured at over 600°F. The scientists were stunned. No one had foreseen this. The liquid remained liquid because of the high pressure of the great depth.

Pieces of the chimneys were brought to the surface and found full of minerals permeated with sulfides. Such minerals were also known to serve as the energy sources of a large group of bacteria, thus explaining why every surface in the smokers' environment was coated with microbes. On successive dives another phenomenon was witnessed. This time it was not fire and brimstone but the proof of life. Microbial life was found to be living amid this hellish embrace, not only on but also in the smokers. A new kind of ecology was being witnessed, composed of species that could not only live in extreme environments but also actually thrive there in great numbers. Unlike all other ecosystems on planet Earth, which are ultimately powered in one way or another by sunlight mediated by photosynthesis, this assemblage of large animals and microbes had, as its ultimate energy source, nothing less than the heat of the earth, and the actual foodstuff of the strange animals was bacteria fueled not by sunlight but by hot, chemical-rich fluids coming up from Hades itself.

The environments around the deep-ocean volcanic rifts that were the home to these newly discovered ecosystems can be described by a single word, *extreme.* Extreme heat surrounded by extreme cold, all in extreme pressure and absolute darkness, and amid toxic-waste chemicals—in short, in conditions seemingly inhospitable to any living thing. Yet within these scalding cauldrons of superheated water, a rich diversity of microbial entities grew and thrived at temperatures far too hot for any animal. It made one think and reconsider the so-called rules of life and the assumptions about where life could and could not live.

Earth, apparently, has at least *two* quite different regimes of life: the traditional one known for centuries, in which plants trap sunlight, and convert CO_2 to living matter, which is then eaten by herbivores, which in turn are consumed by larger and larger carnivores, with all being infested by parasites and ultimately consumed by scavengers, and this new, second system, in which bacteria trap energy from the volcanic vents—no sunlight needed, thanks—with the bacteria taking the place of the green plants in the first and more common system. The microbes that were found to be the lowest link of the food chain in the vents lived off sulfurous compounds found within the vents. In this system the microbes were the equivalents of the plants found everywhere else on the planet's surface. Only slowly did it dawn on most marine biologists that to understand this new system of life, one first had to understand the metabolism of the microbes.

The dive described here was made in the late 1970s, and it is a good place to begin a book about life. The time of these first discoveries is really when the science of astrobiology began in earnest. The entire new suite of creatures found on these dives discredited much

Black smokers as seen from the Alvin *on the deep Pacific Ocean sea bottom.* (Courtesy NOAA/ALVIN)

"common knowledge" about earth life and confounded the then complacent field of biology, which had grown smug in its belief that its practitioners had pretty much found all the basic kinds of life there were to be found. Little did they know that within a few short years of these dives, the entire concept of life's history and classification would be overthrown by a revolution brought about by comparing genes of various creatures. But these reasons, as important as they are, are not why I decided to begin this book's story here, on this deep bottom of perpetual darkness, where temperatures are either too hot or nearly too cold for our more familiar kinds of earth life. Sometime in this century a smaller version of the *Alvin* will dive into one and perhaps two different oceans of temperature and chemistry not dissimilar to our own. Beneath the ice layers of Jupiter's moon Europa and again beneath the ice of Saturn's moon Titan, our species will, like those on the *Alvin* dives of the 1970s, send machines into an alien environment. Will there be life? This is the obvious question. Yet there is another question that is not so obvious but, as we shall see in this chapter, of equal importance, though one that might be very difficult to answer. The *Alvin,* on the first dive onto the black smokers of the deep-sea bottom, encountered a suspended cloud of floating snot that its trained biologists could not even *identify* as life until they were able to conduct high-powered examinations with state-of-the-art instruments. And that experience happened here on Earth. Will we recognize as life *any* aliens that we might encounter in the oceans of Europa and Titan? Life on Earth, even what we call the simplest life, is complicated. But have we set the bar unrealistically high in our definitions of what life might be? Could it be a slow-growing crystal or bits of clay with some scattered carbon molecules attached or even strange compounds of silicon bonded to carbon floating slowly in a pool of supercold oil on the surface of a Saturnian moon? Here we shall explore the first and most critical question facing those on planet Earth who would have the temerity to call themselves astrobiologists: What is life?

So what is life?

Some of the best minds our species has produced have wrestled with the problem without consensus. Our judgment about what is alive on some alien world will all too probably be colored by our membership in the guild of earth life, of life as we know it. But there is surely a great probability that we will eventually encounter what I shall call alien life and not even recognize it as such, or that such life exists, still undiscovered, on our Earth. While a great fear of humanity is that we will—or won't!—find aliens anywhere on Earth or in our solar system, graying heads worry more that we will stumble across life but not even recognize it as such. As we will see, we have a great deal of difficulty deciding if any number of organic-like forms on Earth are alive. So what does this say about our ability to define what is alive or not on alien worlds?

The following statement illustrates just how knotty the definition of life can be: All life-forms are composed of molecules that are not themselves alive. At what level of organization does life "kick in"? In what ways do living and nonliving matters differ?

There is a long list of really smart people who have tried to comprehend and define the nature of life (life on Earth, that is, for few of these savants were considering the bigger picture of life in the cosmos rather than simply life on Earth). The question, What is life? is even the eponymous title of several books, the most famous by the early-twentieth-century physicist Erwin Schrödinger, which provides a great starting point for this discussion. Schrödinger's short book was a landmark, not just for what was written but for who did the writing. Heretofore the fields of biology, chemistry, and physics existed in their own domains, and while the latter two had large and necessary overlaps, the world of the living had been of little concern to these more physical sciences. Schrödinger was among the first of his discipline to break down these walls. He began to think of organisms in terms of physics, and early in his book he took overt notice of the difference between the living and nonliving. While much of the book deals with the nature of heredity and mutation (the book was written twenty years before the discovery of DNA, when the nature of inheritance was still a perplexing mystery), it is late in the book when Schrödinger considers the physics of "living," writing, "Living matter evades the decay to equilibrium," and life "feeds on negative entropy." *Entropy* is the term used to describe how natural systems move from order to disorder. Schrödinger thus saw life as doing the opposite, somehow changing disorder to order, or reversing the natural trend of entropy. Hence his use of the term *negative entropy.* (How like a physicist to complicate otherwise simple things.) Life does this through metabolism, by eating, drinking, breathing, or exchanging material. Is this the key to life? Perhaps—at least to a biologist. But Schrödinger, the physicist, saw something much more profound: "That the exchange of material should be the essential thing is absurd. Any atom of nitrogen, oxygen, sulfur, etc., is as good as any other of its kind; what could be gained in exchanging them?" What, then, is that precious something that we call life, contained in our food, which keeps us from death? To Schrödinger, that is easily answered: "Every process, event, happening that is going on in nature means an increase of the entropy of the part of the world where it is going on. Thus a living organism continually increases its entropy. . . ." Life was thus the "device" by which organisms maintained themselves at fairly high levels of order by continually sucking this "orderliness" from their environment. For all his insight, some of Schrödinger's (and physics's) views about life were naive. From the physics point of view, for instance, life could be understood as a series of machines, all packed together and somehow integrated, functioning in such a way that they, and life itself, could be understood using physical laws. For a half century, then, the question, What is life? could be simply answered: Life is simply an agglomeration of machines that change disorder to order. But in the latter part of the twentieth century, biologists, chemists, and other physicists began first to question and then to amend these views.

The renaissance in understanding the scientific nature of life, stressing that there is surely more to life than biological machines and entropy, was, ironically, led by two other physicists, Paul Davies and Freeman Dyson. Davies, in his 1998 book *The Fifth Miracle*, furthers our understanding of what life is by asking, What does life *do*? If all his answers could be understood as the change in entropy as the result of biological "machines," he would have proved Schrödinger's point. But as Davies showed, there is indeed more. Here are his answers to what life "does":

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 are what we call metabolism, and it is the way that life harvests the negative entropy described by Schrödinger that is necessary to maintain internal order.

Life has complexity and organization.

There is no really simple life composed of but a handful (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.

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 not only that life must make a copy of itself but that it must make a copy of the mechanism that allows further copying; as Davies puts it, life must include a copy of the replication apparatus too.

Life develops.

Once a copy is made, life continues to change; this can be called development. Again, it is a process mediated by the machines of life but also involves processes that are unmachine-like. It is in this area that this new view of life diverges radically from the Schrödinger view.

Life evolves.

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. 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.

Life is autonomous.

This one might be the toughest to define, yet 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. Still, it is that autonomy that again separates life from machine.

It was not only the late-twentieth-century physicists who weighed in, but biologists and even astronomers as well. The great Carl Sagan famously wrestled with the question of what life is, and unlike most others thinking about this topic, who were dealing only with life as it is found on Earth, he came at the problem with a specific goal: He was interested in life beyond Earth, the life as we do not know it. In the mid-1970s Sagan had some very pragmatic reasons to better define life, for as we shall see in chapter 10, he was one of the lead scientists on an ambitious project to land large probes on Mars that NASA accomplished in 1976. Sagan's definition of life, which is still largely taken up by NASA to this day, sees life as *a chemical system capable of Darwinian evolution.*

There are three key concepts to this definition. First, we are dealing with *chemicals,* not just energy. All the *Star Trek* energy beings (how about that Q of *Star Trek*?) are thus cut out. Second, not just chemicals but also chemical *systems* are involved; thus there is an interaction among the chemicals. Finally, our chemical system must undergo 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 descendants, lending the offspring greater ability to survive.

The Sagan/NASA definition has the advantage of not confusing life with being alive. But there are problems under this definition too. For example, one gender of a species composed of two sexes cannot undergo Darwinian evolution and is therefore not alive. But there is a final note of interest about the NASA definition. If we accept it, it means that scientists we meet in the pages to come (specifically, Harvard biologist Jack Szostak and his many confederates) *have already created life in a test tube* because they have succeeded in making short RNA molecules, a chemical system, that undergo natural selection.

So when does life "begin"? By summoning all the various visions of what life is, we can say that life begins in some environment, in which chemistry—to be specific, geochemistry (the sum of the chemical reactions taking place in rocks and the air and water or other fluids above and within)—becomes intertwined with new, self-sustaining, replicating, and evolving chemical reactions among organic molecules on some planet, moon, or other heavenly body. Two different trains of chemistry join the same track, and we have life.

Defining life based on simplicity

So far we have approached the what is life question as a series of definitions. Let us come at this thorny problem from a new angle: What is the simplest assemblage of atoms that is alive? The question lets us look at the various components of a simple life-form and, system by system, ask if it is necessary to keep the whole alive. For life on Earth, we might ask: What is the simplest life-form on Earth, and what does it need to stay alive? We can take these results and ask: Is it possible to conceive of (or construct, but this will be the subject of a later chapter) an alien life-form even more primitive than the simplest life-form on Earth?

The most primitive life found on earth that we all can agree is indeed alive is a large, diverse group of microbes called bacteria. The well-known bacterium *E. coli* can serve as an exemplar of this fascinating zoo of creatures, but any number of other bacteria will do as well, and indeed as bacteria go, *E. coli* is fairly complex. Our first impression is how small this life-form is, and how simple. A rodlike shape is all there is. The outermost part of the bacterium is a cell wall with an interior plasma membrane, which encloses one large, nonpartitioned interior space. This membrane is fundamental for the life of the cell, as it separates the workings of the cell from the outside world and allows there to be interior environments that can have a different chemistry and composition from the exterior world. (Cell walls maintain cell shape and prevent bursting caused by osmotic pressure. They are porous and don't control flow in and out of the cell. The plasma membrane is semipermeable and, although delicate, provides control of substances in and out of the cell.) If we remove this wall and membrane, will the remaining chemicals still live? Clearly not. We know of no life that does not have this property of separating the workings that compose life from the larger environment. Life, then, seems to need some analogue to the cell wall that we see in all known life on Earth.

The major building block of the plasma membrane in our familiar earth life is a substance called a lipid, which has the property of being nondissolvable in liquid water. This is necessary indeed if our cell is to maintain any sort of integrity in a world such as ours where water is pervasive. The molecules making up the membrane are composed mainly of phosphorus, carbon, hydrogen, and oxygen. The fashion in which this structure is constructed gives its property of being insoluble in water. The molecules are distinguished from hydrocarbons (long chains of carbon atoms bonded with lots of hydrogen atoms) by having more oxygen. By itself, a lipid layer would inhibit water and water-soluble substances from passing through it. This would be a disaster for any life having just a lipid wall, and to deal with this, the structure making up the cell wall is more complicated. It is elongate and has one end (with a phosphate molecule attached) that can react with water, while the other end will not. This is necessary for life, for the intake of material for metabolism, and for the egress of potentially poisonous by-products of that metabolism. So most biologists who worry about the What is life? problem are pretty sure that life, any sort of life that we can define, must have some sort of membrane system equivalent to this. As we will see, even this view might be causing us to ignore more interesting assemblages of atoms that might indeed be alive, but we will have to come back to this interesting possibility later. For the moment let us humor the current dogma and ask: Is there any element other than carbon that could be used to make a membrane like that used by earth life? For the conditions that we find on Earth, the answer seems to be no.

Let us continue looking at this particular example of earth life and as miniature adventurers continue our tour of this brave earthling by traveling inward into our cell, passing through the outer membrane system that separates our bacterium from its surrounding environment. The interior of the bacterium is packed with molecules, arranged in rods, balls, sheets, and some far more complex topologies, all floating in a salty gel. If we could see these actual molecules, we would be astounded at the variety. There are about a thousand nucleic acids (these are described in much greater detail later) and over three thousand different proteins. All these are going about some sort of chemistry that, combined, makes up the process that we call life, and one of the major questions facing biology is how so many chemical processes can go on simultaneously in this one-room house.

So far so good. But let us be obnoxious astrobiologists for a moment and turn this humdrum humans-get-miniaturized plot from too many bad B movies into something more interesting. Let us arm our intrepid explorers with the same funky laser weapons (and skintight suits!) given to Raquel Welch and Stephen Boyd in the sixties howl *Fantastic Voyage,* and start shooting up the interior of our bacterium. See that floating globule over there? Zap! How about the complexly folded protein over there? Zappp! How many of the nucleic acids and proteins could we blast into goo and still leave the poor invaded cell alive? (Turning the tables on a life-form that does the same to us on occasion does produce a sense of vicarious pleasure, I must admit.) This is an experiment being conducted—using different techniques from those used by a miniature Raquel Welch, admittedly—in numerous labs in the search to find out what a minimal organism really needs to "live." It turns out that almost any microbe that we enter in this way is fabulously complicated, with a lot more machinery than is needed to be alive. If alive is a one-star hotel room in France, then these are not four-star (not that I have ever had that pleasure, sadly); these are hundred-star deluxe Ritz-Carltons. And these are not even the really deluxe models, the multicellular examples such as ourselves. Earth life: first class life all the way! Or at least the earth life that we have discovered to date. There may actually be ghettos and tenements of life that we have not yet discovered, but they are for another chapter.

Two major and different shapes confront us as we continue to travel through the interior of this tricked-out, chrome-plated earth life bacterial cell. First, there are about ten thousand individual spheres, known as ribosomes, which are distributed rather evenly throughout the cell. If we were to anthropomorphize them, ribosomes would be among the most important characters in a drama that we could title *How Earth Life Evolved*, a play that opened on the earth stage almost four billion years ago to rave notices, and wouldn't we like to know if it made it off Broadway as well, to, say, those summer theater towns of Mars, Venus, Europa, and Titan? The ribosomes are complex characters, as is demanded of any meaty role (pardon the pun here, for they do make the meat that we are composed of). They are made up of three distinct types of the nucleic acid known as RNA and about fifty kinds of protein. But they are not the stars of the show. That distinction is held by the real prima donnas, the second major morphology present: the chromosomes, long chains of DNA complexed with specific proteins.

It is the chromosome that we reach last on our journey through the cell. A long strand of DNA, the key to life on Earth, is made up of only five elements: carbon, phosphorus, nitrogen, hydrogen, and oxygen. It is this molecule that unites all *known* life on Earth and proclaims a common history and ancestry. It is this strand of DNA that governs all, ensuring that the enclosed cell is not just a bowl of chemical soup but also a functioning unit of life. On it is coded all the information necessary to keep this complex chemical factory working and alive.

So what in this cell *is* alive? Rephrased, what is life anyway? Again, if we really do take this junk out, bit by bit, at what point does the poor victim die? Our bacterium is composed of inanimate molecules. A DNA molecule is certainly not alive in any sense that any rational person would accept. The cell itself is composed of myriad chemical workings, each, taken alone, but an inanimate reaction of chemistry. The apparent increase in order found within our cell—the loss of entropy, the negative entropy of Schrödinger's of so many years ago—does not contradict the second law of thermodynamics (which states that every chemical reaction results in a loss of energy) because it is accompanied by an increase in *disorder* around the cell itself.

Can it be said that *nothing* is alive but the whole of the cell itself? This appears to be the case for this bacterium (except if it has a few viruses within it, of course, but we will come back to this very controversial point a few paragraphs hence), and if we are to understand how life first arose, we need to find the minimum cell that can accomplish this. How small, with how few molecules and reactions and information, can it be and still have this elusive property of life? Moreover, if this is life, how can there be a similar process to living without the various molecules and chemical reactions that are part of this system as it extracts order from its surroundings, reproduces, evolves? Either we change the definition of what life is, or we are confronted by some minimum yet enormously complex system of matter and energy flow. So to make an alien, we need to change only the structural components, not life itself, it seems. Let me make the first of many obtuse conclusions: There are alien body forms, not alien life. There are many ways to cause inanimate matter to take on the property of life. But there is only one "species" of life itself.

One of the pressing problems in looking at this simple cell is that, when examined in detail, it is in no way simple. Freeman Dyson has explicitly looked at this aspect of modern life, asking: "Why is life (at least life today) so complicated?" If all known bacteria contain a few thousand molecular species (coded by a few million base pairs in the DNA), it looks as if this might be the minimum-size genome. Yet all bacteria come to us today at the end of more than three (and perhaps more than four) billion years of evolution. How simple might the first organisms have been, and how simple might a microbe on Mars, Europa, or Titan be? Are we blinded by earth-style complexity when there can be much simpler life? This is why we linger at length over this seemingly trivial but obviously complicated matter. What indeed is the simplest assemblage of chemicals that could be considered alive? Perhaps the simplest earth life is among the most complicated of life-forms in the cosmos, and we earthling students of life are blind to that fact. The answer is not yet known. But there are at least a few people working on it, most in the fraternity of astrobiology. My sense is that there is a whole diversity of life simpler than the cells we deem the simplest. So here I propose the first heresy of many to come: that all around us are just such "simpler" well-known life-forms that we do not consider to be living. Not so. Viruses are alive.

The case for a living virus

Case in point, there are biological entities simpler than bacteria on Earth. Much simpler, in fact. Viruses, the scourge of humanity, the scourge (but perhaps the creator as well) of all life on Earth, clearly have a huge effect on life. But is a virus itself alive? This question has great importance in understanding the evolution of life on Earth as well as in classifying earth life, for if viruses are deemed alive, fundamental changes must be made to the classification of "life as we know it." Here I will make that case.

A virus is very small. Typical viruses are from 50 to 100 nm in diameter, where *nm* stands for "nanometer," or 10^{-9} meters. At this size many millions of viruses can fit on the head of a pin. They come in two general types: One group is enclosed in a shell of protein; the second in both a protein shell and a membranelike envelope. Within this covering is the most important part of the virus, its genome, made up of a nucleic acid component. It turns out that there is an amazing variety of genome types in viruses. In some there is DNA; in others only RNA. The number of genes also varies widely, with some having as few as 3 genes and others (such as smallpox) having more than 250. In fact, there is a huge variety of viruses, and if they were considered alive, they would be classified across a great taxonomic spread. But common wisdom treats them as nonliving.

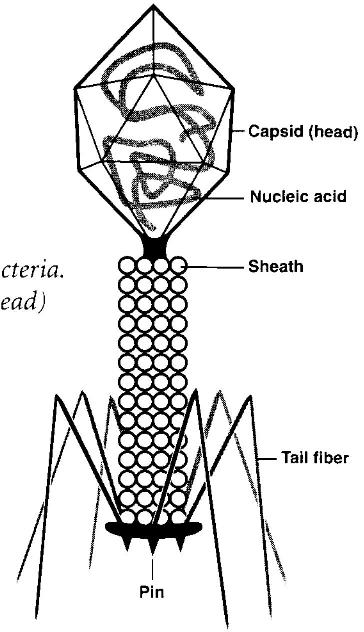


Diagram of a virus that attacks bacteria. Simpler forms are only a capsid (head) containing nucleic acid.

The viruses that contain only RNA may be important in understanding questions surrounding the origin of life on earth. RNA viruses show that RNA by itself, in the absence of DNA, is capable of storing information and serving as a de facto DNA molecule. This finding is strong evidence that there may have been an RNA world before DNA and life, at least as we know it, originated. And there is an even more striking implication of the presence of RNA viruses. Since viruses are parasites, it may be argued that there may be as yet undiscovered RNA life-forms that are not viruses on our planet, with the RNA viruses as their parasites, as well as a proof of existence. Thus there may be simpler life than even a bacterium (but not as simple as a virus) living unknown among us.

All viruses are considered parasites. They are technically termed obligatory intracellular parasites because they are unable to reproduce without host cells. In most cases, viruses infiltrate cells of living organisms, hijack the protein-forming devices within the invaded cells, and start making more of themselves. They turn an invaded cell into a virus-producing factory. It is all too well known that viruses have a huge effect on the biology of their hosts.

We can use the various aforementioned definitions of life to decide if viruses are alive or not. The greatest argument against including them in the land of the living is that they need hosts to replicate; they are unable to replicate on their own. But it must be remembered that viruses are *obligatory* parasites, and parasites tend to undergo substantial morphological and genetic changes in adapting to their hosts.

Freeman Dyson considers it highly unlikely that viruses are remnants of primitive cells that existed prior to the evolution of life as we know it, and thus, in his view, they are not "missing links" between the dead and the living. Not everyone agrees with his argument, and as we will see in the next chapter, there is an enormous diversity of viruses just now being discovered, especially in the ocean, and many of these show some very peculiar and tantalizing traits. One group of RNA viruses studied by Alan Weiner and Nancy Maizels in 1987 were even described as living fossils of the RNA world! I will make this same argument, acknowledging here that Weiner and Maizels realized this many years ago.

That viruses may in fact be "alive" is also advocated by Martin Olomucki in his useful book *The Chemistry of Life,* in which he notes: "It is not always easy to draw a clear line between the largest viruses and the smallest primitive parasitic bacteria." One such is the infectious agent of parrot disease, or psittacosis, which was long thought to be a virus but which, under closer scrutiny, was identified as the primitive prokaryote *Chlamydia.* This very nasty bug is *very* small even for a microbe, 0.2 to 0.5 thousandths of a millimeter, and contains DNA, RNA, and a few enzymes. What it does not have, however, is any way to replicate itself outside its host. It is thus just like a virus, yet *Chlamydia* is definitely classified as living. By looking at a number of more complicated viruses, Olomucki concludes: "[Y]et, despite the poverty of its constitution, the virus cannot be considered merely a chemical substance; viruses are really and truly living objects." But if so, where do we put them in the classification of earth life? They are not Bacteria, or Archaea, and certainly not Eukarya, the three great domains of life (we revisit the concept of a domain in chapter 2 as well as the three domains of life on earth mentioned here). So what are they?

No one disputes that a virus is a parasite. So let us ask, are other parasites alive? Parasitism, which is essentially a highly evolved form of predation, is generally the result of a long evolutionary history. Parasites are not primitive creatures. But like our viruses, they have stages that do not seem fully alive. *Cryptosporidium* and *Giardia,* for instance, both well-known (and nasty!) parasites on humans and other mammals, have resting stages that are as dead as any virus outside its host. Without the hosts, the parasites mentioned earlier (and thousands of other species as well) will not live. Accepting these eukaryotic parasites, but then rejecting viruses as living, is not very scientific, in my opinion. If one group is, both are. So in this book, using the logic of those who study animal parasites, I will promote the heresy (to some anyway) that they are alive. These parasites are certainly alive, yet they cannot replicate outside hosts, just like viruses. And if we accept that viruses are alive, we must radically reassess the tree of life as it is currently accepted.

Are prions alive?

The existence of prions is also a test of the what is alive question. Prions are small and mysterious "organisms" that cause a number of truly hideous diseases, the most notorious being scrapie (in sheep) and mad cow disease, which can infect humans. When these diseases were first discovered, it was assumed that the infectious agent was a virus. Eventually the "agent" was discovered and named a prion, short for proteinaceous infective particle. Prions test negative for nucleic acids of any kind and thus have neither DNA nor RNA. It is conjectured that they are pure proteins, and there is now much evidence for this protein-only theory of prions. In fact, recombinant prions that are infective to mice have now been made. The mechanism of propagation is believed to involve the ability of the misfolded form of a normal cellular prion protein to cause a shape change in that protein, converting it from the normal shape (harmless) to a new shape that causes great harm to the host, if that is the correct word for the organism containing these "bad" prions. Prions are made/propagated in the cytoplasm in yeast and are thought to be made/propagated on the cell surface in mammals.

Replicate they do, when they invade nerve cells of their hosts and, like a virus, induce the host cells to start making lots of them. Like the presence of RNA viruses, the existence of prions has interesting implications. They may prove that protein alone can act as both software—coding information—and hardware. Do prions metabolize? Doubtful, since the protein-only theory seems to hold, and it is difficult to envision how a single protein could metabolize. Do they evolve? Very possibly, since the different strains are not equally efficient, and only one will propagate in a single host when a mixture is present, but each will propagate in a single host if introduced serially. Are they alive? Maybe. But like viruses, they cannot be placed into any standard taxonomy of life on Earth.

A heretical position

As we will see, one of the major definitions of life is that it is cellular. This is a point strongly made by biologists Lynn Margulis and Dorian Sagan in their book *What Is Life?* I disagree with this position. Here I take a page from musings by biologists Carl Woese and John Baross.

What if life can be an ecosystem as well as a cell, given the right kind of ecosystem? Early in earth history, in some primordial ooze, we may have had *thousands* of different kinds of protocells, naked genes, viruses, viruslike things, prionlike things, raw organic molecules, and on and on. By themselves none are alive. Taken altogether, the mishmash fulfills all requirements of life. This is my view too. If we landed on Titan, and a similar type of "organism," formed of myriad, dispersed, but chemically interacting components, were present, would we even recognize it as life? For that matter, if in some time machine we went back to the early earth, would we recognize life when it first started? Doubtful. Should we give a name to such life? Probably. But I'll be busy enough naming things in the pages to come that I'll pass on this one.

We might summarize the what is life question by suggesting that our view of life is enormously colored by our experience of being complex organisms in a world of complex organisms. Life can be simpler than the deluxe earth models, as evidenced by viruses. And it may well be that even viruses are very complex forms of life compared with varieties of life that we might find beyond Earth or hidden and unrecognized here on Earth. There is an enormous diversity of animate chemistry, at least theoretically. Ever since Darwin, it has been assumed that all our earth life is derived from a single common ancestor. But is this correct? What made Darwin think so, and how has that view changed with the revolutionary advancements we have made in microscopy in the minute chemical parsing of cells? These will be the subjects of the next chapter, where we go from defining life to looking at the nature of earth life. It used to be that these were one and the same. Once we can handily characterize what earth life is, we can then attack the problem of what earth life is *not*, life that is not earth life as we know it—like viruses, for instance—of the earth, but not earth life according to current biology. Viruses are thus aliens, our first of this book so far.

Chapter 2

What Is Earth Life?

This four-letter alphabet provides the basis for the common DNA language of all living organisms on Earth. They all share the same four-letter alphabet and DNA language, which is convincing evidence that we are all descended from one uniquely successful ancestor, whether that ancestor first appeared inside a comet or in Haldane's primeval soup or in Darwin's warm little pond.

—John Gribben

We humans have long and intuitively known that we each are the product of nature and nurture, a melding of our genes and the events in our lives and even the events in history before our lives. So too it must be for the life on any planet or moon. That has certainly been the case for earth life, which comes to us battered and melded by history. In the last chapter we looked at what life is. In a nutshell, life replicates, metabolizes, and evolves. So, in this chapter, let us establish what *earth* life is—that good old (really old) familiar stuff that we belong to—and ask how not only genes but also history have colored it. Seems like a simple enough prospect, with all the life there is around us to use as an example. But that is part of the problem: There is *so* much life on Earth and in such diversity of shape, habitat, and chemistry that coming up with a single definition requires some thought. Nevertheless, it's a pretty straightforward task. But there is a second and paradoxical aspect to this chapter's main task, one that has the faint whiff of irony. For all the thousands of pages written in pursuit of classifying the myriad aspects of life on Earth, there does not seem to be a formal published description of what earth life (or at least the kind of earth life that we belong to) *is*, so that we can know what it is *not*. It is just referred to as life, and since few, if any, of the army of taxonomists, those biologists preoccupied with classifying earth life, have ever considered life off the planet or had the temerity to question the ironclad doctrine delivered by Charles Darwin that all life on Earth comes from a single ancestor, somehow, no formal description of our kind of life has been made. There is not even a formalized taxonomic category, such as genus, species, or kingdom, that could be used to house such a definition. In this chapter we shall remedy that, to my surely everlasting infamy among classically trained biologists.

The construction of habitable planets in the solar system

Time is something that is integral to the story to come. Here and there I will have to refer to geological time, rather than the years in the past in which some event happened. Most of the events discussed here took place before the advent of animal life on Earth and hence at a time before common fossils. While the differentiation of rocks and time based on fossil content works quite well for the long interval of time since the rather sudden appearance in the rock record of larger fossils, the time before fossils—by far the longest interval of earth history—is more difficult to subdivide. This pre-Cambrian time is broken into three major divisions, named (from oldest to youngest), the Hadean, Archean, and Proterozoic eras. The Hadean was the time before life and any sort of abundant rock record. The Archean era began with the first appearance of life and a rock record but ended not with any biological event but with a series of physical changes to the earth. The succeeding Proterozoic was a time dominated by microbes, but near its end the first animals evolved, and the boundary between the Proterozoic and the succeeding Paleozoic is marked by the Cambrian explosion, when skeletonized animals appeared in large numbers for the first time. The Hadean, Archean, and Proterozoic eras are thus long intervals of time with few definable events.

So what was the planetary history that affected earth life? At the risk of departing from our main narrative, let us take a detour and look at how dear old Mother Earth came to be.

Life seems to have appeared on this planet somewhere between 4.1 and 3.8 billion years ago, somewhere near the end of the Hadean or early in the Archean era—or some 0.5 to 0.7 billion years after the earth originated, but 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 find on the planet are from rocks about 3.6 million years of age and look identical to microbes still on Earth today. There may have been earlier types of life not now represented on Earth (or not yet found, but that is part of our story), but our present knowledge suggests that simple oval or spherical bacterial-like forms were the first to fossilize and may have been the shape of the first life on earth as well.

Time (in millions of years ago)	**Era**	**Events**
65 to present	Cenozoic	First large mammals to end of terrestrial communities. End of ice age
250 to 65	Mesozoic	First dinosaurs to Cretaceous mass extinction
543 to 250	Paleozoic	First skeletonized animals to Permian mass extinction
2,500 to 543	Proterozoic	First eukaryotic cells to first skeletonized animals
3,800 to 2,500	Archean	First life to first eukaryotes
4,600 to 3,800	Hadean	Origin of earth to origin of life
Before 4,600	No name	Solar system (and planet Earth) forms

Table 1. *The Geological Time Scale*

While life may be old, our planet is much older yet. Earth formed about 4.5 to 4.6 billion years ago from the coalescence of various size planetismals or small bodies of rock and frozen gases. For the first several hundred million years of its existence, a heavy bombardment of meteors continuously pelted the planet with lashing violence. Both the lavalike temperatures of the earth's forming surface as well as the energy released by the barrage of incoming meteors during this heavy bombardment phase would surely have created conditions inhospitable to life. The energy alone produced by this constant rain of gigantic comets and asteroids prior to about 4.4 billion years ago would have kept the earth's surface regions at temperatures sufficient to melt all surface rock and keep it in a molten state. There would have been no chance for water to form as a liquid on the surface. Clearly there would have been no chance for life to either form or survive on the planet's surface.

The new planet began to change rapidly soon after its initial coalescence. About 4.5 billion years ago the earth began to differentiate into the different layers. A lower-density region called the mantle surrounded the innermost region, a core composed largely of iron and nickel. A thin, rapidly hardening crust of still-lesser-density rock formed over the mantle, while a thick, roiling atmosphere of steam and carbon dioxide filled the skies. In spite of its being waterless on its surface, water was associated with the planet. Great volumes of water would have been locked up in the interior of the earth and would have been present in the atmosphere as steam. As lighter elements bubbled upward and heavier ones sank, water and other volatile compounds were expelled from within the earth and added to the atmosphere. The constant bombardment by giant comets and asteroids lasted more than a half billion years and finally began to diminish around 3.8 billion years ago as the majority of meteors were gravitationally pulled into the various planets and moons of our solar system. During the heaviest impact period the steady bombardment would have cratered the planet in the same manner as the moon. Yet the comets and asteroids raining in from space delivered an important cargo with many of these titanic impacts. Some astronomers believe that much or most of the water now on our planet's surface arrived largely through the incoming comets; others think that only a minority of the earth's water arrived in this fashion. There is still no resolution to this question, although some new measurements of comets suggest that they were not the main source of our water, the elixir of life on Earth and perhaps life everywhere. And the comets brought other components for life, including carbon compounds. Instead of Earth going to the chemical supply store for the ingredients of life, the store came to it.

Comets are made up mainly of volatiles, such as water and frozen carbon dioxide, and there is no doubt that a good many of them hit the early earth. Study of carbonaceous asteroids and comets shows that many carbon compounds rained onto the surface of the earth in the earliest ages of the solar system. And not just on Earth. Looking at the moon and Mars reveals the ubiquity and abundance of craters. Enormous numbers of comets rained down onto all the planets and moons, bringing the stuff of life to every moon and planet in the solar system. For some, such as Mercury and the outer gas giants, these gifts of life's components were entirely superfluous. But for Earth and perhaps Venus, Mars, Europa, and Titan, the five bodies with life (or the best chance of having had it or still having it), the rain of comets was probably instrumental in whatever organic evolution that occurred.

Prior to 4.4 billion years ago these cargoes of water slamming into the earth at least would have turned instantly to steam because of the high temperatures on the surface. Perhaps the same happened on Venus and Mars. But Earth and its inner and outer sister planets gradually began to cool as their heat dissipated into space. As early as 4.4 billion years ago surface temperatures on these three planets might have dropped to below 100°C, and for the first time liquid water would have condensed from steam onto our planet's surface, in the process successively forming ponds, then lakes, and seas, and finally a planet-girdling ocean. It is thought that the same happened on Mars and Venus. If seen from space, there may have been *three* blue jewels orbiting the sun back then instead of the single blue planet of the present day, our water-drenched Earth. A watcher from Earth back then would have remarked on the beauty of blue Venus and blue Mars. The study of ancient sedimentation suggests that by slightly less than 3.9 billion years ago, the amount of oceanic water on Earth may have approached or attained its present-day value, along with that on Mars and Venus. This time might have been the period of the most widespread habitability in our solar system. But they were not tranquil oceans on these planets, or oceans even remotely familiar to those of today.

We have only to look at the moon to be reminded of how peppered the earth and its oceans were during the period of heavy impact, between 4.4 and 3.9 billion years ago. Each successive large-impact event (caused by comets as large as 500 kilometers in diameter) would have partially or even completely vaporized the oceans. Imagine the scene as viewed from outer space: the fall of the large comet or asteroid, the flash of energy, and the vaporization of the earth's planet-covering ocean, to be replaced by a planet-smothering cloud of water vapor and rock-filled steam heated (at least for some decades or centuries) far above the boiling point of liquid water. It is difficult to conceive of life, whatever its forms, surviving anywhere on the planet during such times, unless that survival occurred deep underground.

NASA scientists have completed mathematical models of such ocean-evaporating impact events. The collision of a 500-kilometer-diameter body with the earth results in a cataclysm almost unimaginable. Huge regions of the earth's rocky surface is vaporized, creating a cloud of superheated "rock gas," or vapors, several thousand degrees in temperature. It is these vapors in the atmosphere that cause the entire ocean to evaporate into steam. Cooling by radiation into space would take place, but a new ocean would not rain out for at least several thousand years after the event. Much of the revolutionary detective work behind these conclusions was described in 1989 by Stanford University scientist Norman Sleep, who realized that impacts of such large asteroids or comets could evaporate a ten-thousand-foot-deep ocean, sterilizing the surface of the earth in the process.

It is ironic that the comets may have brought some of the earth's life-giving liquid water, the necessary prerequisite of life, and then taken that gift away for a time with each successive large-impact event. Yet it is not only water that these comets may have brought. They played a role in determining the chemical evolution of the earth's crust. And they perhaps brought another ingredient in the mix we call life: organic molecules or even life itself onto our planet's surface for the first time.

About 3.8 billion years ago, at the end of the period of heavy bombardment, our world would surely still appear alien to us. Even though the worst barrage of meteor impacts would have passed, there still would have been a much higher frequency of these violent collisions than in more recent times. The length of the day was far different, being less than ten hours long, because the earth was rotating far faster than it does today. The sun would appear much dimmer, perhaps a red orb of little heat, for it not only was burning with far less energy than today, but it had to shine through a poisonous, riled atmosphere composed of billowing carbon dioxide, hydrogen sulfide, steam, and methane. In such an environment we would have had to wear spacesuits of some sort, for only tiny traces of oxygen were present. The sky itself would probably have been orange to brick red, and the seas, which surely covered most of the earth's surface (save for a few scattered low islands) would have been muddy brown and clogged with sediment. Yet perhaps the greatest surprise to us would be the utter absence of life. No trees, no shrubs, no seaweed or floating plankton in the sea; it would have seemed a sterile world. Somehow the fact that we have not yet detected life on Mars seems consistent with its satellite images. A waterless world fits our picture of a lifeless world. But even when the young earth was covered with water, it was still devoid of life. However, it was not for long.

For Venus and Mars at this time a different history was playing out. Mars, the wet planet, was dying and drying out. On both planets their blue oceans were lost to space. Gradually, Mars became a cold desert and Venus an unbelievably hot greenhouse. From that time on, the surface of neither planet would have been fit for life, as we know it anyway. But on both places there remained potential refuges, as we will see later.

Most scientists are confident that life on Earth had already arisen 3.8 to 3.9 billion years ago, at about the time when the heavy bombardment was coming to an end. Because of the suspected similarity in conditions on Mars and Venus at the time, there may have been life on these two worlds as well. Indeed, the very violence of the impacts at that time may have seeded each of the planets with life from one of them, a process called panspermia that we will revisit later. We earthlings might really be Martians, or Venusians, or their life might have been from Earth. Or perhaps life arose three separate times. We have no shortage of hypotheses to be disproved.

The evidence indicative of earth life's appearance is not the presence of fossils, but of isotopic signatures of life extracted from rocks of that age in Greenland. The oldest rocks on Earth that have been successfully dated using radiometric-dating techniques are mineral grains of zircon, yielding ages of about four billion years. The Greenland rocks (from a locality named Isua) are thus only slightly younger. The Isua rock assemblages include sedimentary (layered rocks) and volcanic rocks and have yielded a most striking discovery. They contain isotopes of carbon, life's most diagnostic elemental signature, suggesting that they were formed in the presence of life. The isotopic residue in the Isua rocks is an excess of the isotope carbon-12 as opposed to carbon-13. A surplus of carbon-12 is found today in the presence of photosynthesizing plants, since all living organisms show an enzymatic preference for "light" carbon. The inference is that if early life existed at Isua, it may have used photosynthesis for its energy sources. But there is no fossil evidence that life existed this long ago, only this enigmatic and provocative surplus of a carbon isotope that in the present world is a sign of life's presence. If the excess of light carbon isotope is indeed a reliable indication that ancient life existed at Isua and perhaps elsewhere on the earth as early as 3.8 billion years ago, it leads us to a striking conclusion: Life seems to have appeared simultaneously with the cessation of the heavy bombardment period. As soon as the rain of asteroids ceased, and surface temperatures on Earth fell below the boiling point of water, life seems to have appeared. But how?

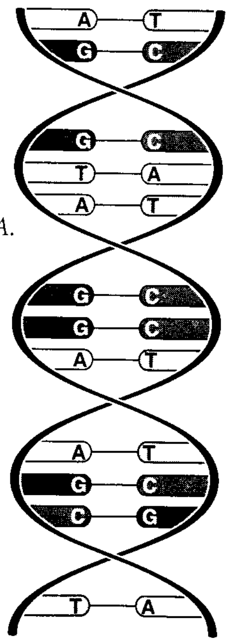
There are still more questions than answers about life's origins on earth, and obviously nothing but questions concerning potential life on Mars and Venus. Yet the sophistication of the questions now being addressed by a legion of interested scientists tells us that we are well along in the investigation. Among the most pressing of these questions: Did the origin of life occur in only a single or in several settings? Did the key chemical components, the building blocks, come from different environments to be assembled in one place? Was life's origin deterministic—i.e., could there be different environmental conditions producing the same molecule of life, the familiar DNA? Were the individual stages in the origin of life (such as the formation of amino acids, then nucleic acids, then cells) dependent on long-term changes in the earth's environment? Did the origin of life change the environment such that life could never originate again? At what stage did evolution take over to guide the development of life? Perhaps most interesting of all, can we infer the nature of the settings of life's origin from the study of extant organisms, creatures living on Earth today?

But what really *is* earth life?

No one would dispute that planet Earth is besotted with life. From that long-ago time when earth life first formed, we have gone from

some first cell to millions of species. From the deepest ocean depths to the highest mountain crags, it is difficult to find any habitat that does not at least harbor a smattering of microbes, and when we reach the richness of the African plain, or tropical rain forest, or coral reef habitat, the cornucopia that we call life is everywhere apparent. It is this very richness that has caused no end of dispute and work for those biologists concerned with classifying it all. But even with all this diversity, all life yet discovered shows a unifying characteristic: It all contains DNA. So perhaps this is how we should define earth life.

Deoxyribosenucleicacid, or DNA, is something that we encountered first in biology class and then constantly in the news. If nothing else, the infamous O. J. Simpson trial brought this peculiar molecule to the fore of our consciousness. Detecting the identities of criminals, establishing paternity, following the endless crime



The double helix of DNA.

scene forensics of the scandalous trial de jour, DNA as a concept cannot be escaped. Yet it is complex, and its actions even more so, and since so much of this book deals with it in one variation or another, it might be profitable to describe it in detail.

Composed of two backbones (the famous double helix described by its discoverers, James Watson and Francis Crick), this complex molecule 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 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 only a single strand, or helix, rather than the double helix of DNA. Also, RNA has one different base from DNA.

There are four kinds of RNA, which Freeman Dyson (in his *Origins of Life*) has analogized with the hardware and software of a computer system. DNA is clearly always software, and proteins are usually hardware (with the notable exceptions of prions and the possibility that ancient organisms used proteins as genetic code, making it software). RNA has the interesting characteristic of being either hardware or software and, in some cases, both at the same time. RNA occurs in the world in four different forms, with four different functions. First, in some viruses there is genomic RNA, which acts like DNA in storing genetic information and containing genes. In the AIDS virus, RNA makes up the entire genome. In this case the RNA acts as software. Second, there is ribosomal RNA, a structural part of ribosomes, the tiny organelles within cells that make proteins. This is a case of RNA clearly acting as software. Third, there is transfer RNA, the hod carrier that takes amino acids to ribosomes for protein synthesis, and as a material conveyor it is hardware. Finally, there is the most interesting of all the RNAs, messenger RNA, which conveys instructions to the ribosome from the genomic DNA. In this it acts as software, but it has been shown that it can also act as a catalyst both for protein formation and for its own splitting and spicing and thus acts as software *and* hardware at the same time.

Understanding RNA, its use and evolution, is key to understanding life on Earth, and perhaps not only earth life but other types of life as well. In earth life DNA makes RNA, which makes proteins. This is known as the central dogma and was first defined by Francis Crick (who later admitted that he regretted using the term *dogma* in this definition). But as we will see, RNA might have preceded DNA during earth life's origin. Most RNA is used as a messenger, sent from DNA to the site of protein formation within a cell, where the specific RNA gives the information necessary to synthesize a particular protein. To do this, a double-stranded DNA partially unwinds, and a single-stranded RNA forms and keys into the base pair sequence on the now-exposed DNA molecule. This new RNA stand matches with the base pairs of the DNA and in so doing encodes information about the protein necessary to be built. This brings us to the subject of genes.

DNA provided the answers to many of the mysteries of genetics, answering the question, once and for all, about what a gene is. Watson and Crick made the great discovery, one that launched an enormous revolution in biology, and it was announced in a paper in the journal *Nature* that was 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 Crick who suggested that the sequence of bases is a code, the so-called genetic code, that somehow provides information for the formation of proteins, one amino acid at a time. The information coded has to be read (transcribed) and then translated into proteins. That is where RNA comes in. Life as we know it uses twenty amino acids. Not nineteen. Not twenty-one. *And always the same twenty!* If we suddenly found (or made!) life that used a twenty-first amino acid, for instance, this would be a good reason to rejoice in the discovery of alien life. There is a transfer RNA molecule specific for each of the anointed twenty of the amino acid clan. Once alerted by Chief DNA that a particular amino acid from the twenty is needed for a specific protein to be built, our transfer RNA goes out into the cytoplasm of the cell interior, scavenging for the particular amino acid that it alone can carry. Once the amino acid is found, this transfer RNA then heads to the ribosome with its burden.

The code is elegant and can be analogized to Morse code, itself just a system of dots and dashes that is able to string together long and complex messages. Crick realized that the different combinations of bases lined up on the DNA molecule could specify each of the twenty amino acids used by life on Earth. But actually making the proteins took place in the small spherical bodies within the ribosomes. Therefore, some link had to be made between the DNA and the protein formation centers. This is the job of messenger RNA molecules. Thus DNA codes for RNA, which codes for proteins. This, then, the central dogma of molecular biology, may also be called a central characteristic of earth life.

How to define earth life

We are starting to compile a large number of specific characteristics that our kind of life uses to stay alive. Let us look at the genes of earth life in more detail, so as to understand how they might differ in nonearth life. First of all, 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-dimensional shape determines their actions.

So, how does DNA specify a particular protein? A typical protein might be made up of a hundred to more than five hundred amino acids, 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 a hundred to five hundred 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.

So, earth life has DNA, and RNA, has a specific code, and uses tiny structures in the cell called ribosomes to make another characteristic of earth life, proteins.

The code itself is important to look at, for it is one area that could be changed to produce alien life or at least form a DNA life unlike that on Earth. The fact that all our bodies are made up of proteins constructed from twenty different amino acids, but always the same twenty, is itself a characteristic of earth life. Again, using different, more, or fewer amino acids would certainly seem to qualify a life-form as being unearthlike.

This information flow goes only one way: from DNA to RNA. 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.

Our description has gotten more complex. We need to incorporate the code that is used and the twenty amino acids that we are made of. Now we have more to play with: We have a specific information-carrying molecule (DNA) that is found in a structure (a chromosome) that (using RNA and ribosomes) works to produce a slew of proteins, all made up of twenty, only twenty, specific amino acids (these can be found in any biology text), using a particular code of nucleotides to specify an individual amino acid.

This much information is no longer a rough sketch of a suspect in a police report but a fingerprint. Is this fingerprint unique to life on Earth or even to all life on Earth?

A new classification for life

What else can be used to diagnose (the formal term used by taxonomists) this taxon (any one of the formal units of biological classification) that constitutes the common form of earth life? Again we have to hedge, for as we shall see in chapter 5, there are other forms of life, other taxa, distinct from those of our still-unnamed life as we know it, that have existed in the past and may exist now on the planet, as well as artificially produced life that does not meet this diagnosis. We also have to hedge about the taxon, for without giving away too much of the surprise, not only is there not yet a taxon for life as we know it, but there is not even a taxonomic category yet defined that would include all of this life as we know it. So let us look at what else there might be that categorizes this group of life and then look at the currently accepted tree of life and as well at how such trees are constructed. That done, we can start tree building.

Having 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 specific wall or membrane structure and the specific solvent are also features that we can use to identify common earth life. In a recent insightful essay in *Current Affairs,* biochemist Steven Benner (a member of my University of Washington NASA Astrobiology Institute team who appears again later) and two colleagues have described our familiar life in even more basic chemical terms. They see life as needing isolation of some sort, within a membrane or bounding domain that is chemically produced. But they also point out that isolation does not necessarily require putting guts in a 3-D box. It can be achieved on a two-dimensional surface, and this understanding has led to new ideas about the interaction of organic molecules and mineral surfaces that have greatly expanded our view of how life came about and how it might be on non-Terran habitats.

Benner et al. also suggest that a requirement of life is some sort of scaffolding, for building blocks of our life structure and for holding 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 were side branches on which carbon compounds could bond. One such material is called oligosilane, which is made up of silicon atoms that are bonded together in chains (but that also have side chains that are not composed of silicon). These have the potential to make membranes that would be very different from the cell wall membranes used by our familiar carbon life. We can add to our definition that our familiar earth life has a plasma membrane, composed of a cell wall composed of material known as phospholipid bilayer and membrane protein and a specific solvent, water. Now we have a description of this kind of life. Let's give it an informal name, so we can dispense with the very clumsy life as we know it, earth life, or DNA life that we have been using to this point. There could be any name, but following old practice, let us utilize the Latin for earth (*terra*) with the suffix used to denote life (*oa,* meaning "life") and combine this into the name Terroa. It could be Terraoa, but that seems a little too Polynesian or denoting terrorists of some sort. So: Terroa. Earth life. The life as we know it kind of earth life anyway.

There are lots of Terroans around us, and there have been for at least 3.7 billion years. But not always. Sometime, in the deep past of our planet—perhaps just more than 3.7 billion years ago, perhaps more than 4 billion years ago—there was life but not Terroan life on Earth. This was before some first cell combined all the DNA and

RNA apparatus, membranes, water, enzymes made from the twenty amino acids, and so forth—the whole shebang that we DNA life-forms use—to form the very first Terroan, living in a fashion that might not seem strange to those who know the ecology of microbes in the present day. There was some first cell of some first Terroan species, the only one of its kind. There is no fossil that memorializes it. Nevertheless there must have been some first example of what we now call earth life. It and the rest of its species, for there were more than one of these little urchins, even have a name: LUCA, for last universal common ancestor.

Other terms have been used to describe this ancient parent of us Terroans. The pioneering microbiologist Carl Woese first called it the progenote. But the meaning of *progenote* seems to denote a particularly primitive ancestor, one much simpler than actual cells. This would not be the first species that we could call earth life, but it is something leading up to it. LUCA is viewed as a microbial common ancestor, resembling either Bacteria or Archaea.

Was our first Terroan the first life? Was it thus lonely? Definitely not, on both counts. Our LUCA did not pop out of the firmament fully formed. It had ancestors. And they were not Terroans and thus need their own name. In fact they were aliens, definitely life as we do *not* know it. But that is part of our story to be taken up in the next chapter. At the moment let us contemplate LUCA, our first Terroan, a unique kind of species on Earth, but probably not a unique species of life. LUCA was surely surrounded by a huge diversity of life. There would have been other true cellular life, like LUCA, as well as a whole zoo-full of other life-forms and unloving but organic molecules, a real bouillabaisse of early life on Earth in the primordial soup (if there was a soup, which some now disbelieve).

In all this surely great slew of life-forms, LUCA was indeed unique but probably not for long. The earth back then, as now, was a place of many habitats and with many ways that a resourceful form of life (like our little LUCA, the most modern life on the planet, a veritable prodigy on that ancient earth) could acquire energy and material for growth. Natural selection would have stoked the fires of the speciation process, and where there had been but a single species with DNA and proteins as we use them, there now would have been two, and soon after, many, many more. Meanwhile, as our sharp little Terroans ran rings around the poor RNA life and other losers, wholesale extinction of early life-forms surely took place. The burning of the great Roman library in Alexandria was as nothing compared with the loss of information during this first great mass extinction on earth, as Terroans co-opted the planet's resources in ruthless Darwinian fashion, and untold genomes of pre-Terroan life blinked out of existence. The standard story is that at the end of this evolutionary winnowing, only the Terroans were left as life on Earth. But I dispute that. Like the coelacanth fish, a few of the more ancient kinds of life hung on. Indeed they are among us now.

Today we define species as composed of individual organisms that are capable of interbreeding successfully. The species is also the basic unit in life's classification, the method that biologists use to organize the enormous diversity of life on Earth. Because the evolutionary process causes one or more species to arise from other coexisting or preceding species, many share ancestors. Blocks of species are thus united by common heritage, just as the siblings of a family share a set of parents. These groups of related species are called higher taxa.

The Swedish naturalist Carl Linnaeus developed the modern way of describing organisms and of organizing both the species and the higher taxa. In 1758, under the title *Systema naturae*, Linnaeus published one of the great revolutionary works of science. He swept aside the old ways of naming and classifying organisms and heralded in an era that continues to this day. Very few other scientific advances from the middle of the eighteenth century have worn so well. Linnaeus proposed a binomial system for naming organisms, replacing the old system of a single common name for every living creature. Each species has two names, its genus and species names. To avoid further confusion, the name of the scientist formalizing the name is appended at the end along with the date on which the species was described. Linnaeus also grouped blocks of species into higher categories, on the basis of degree of similarity. In so doing, he erected the major taxonomic categories.

We live on a planet with millions of species. If they just appeared through some sort of divine creation, we would expect a lot of unrelated forms. But anyone can see that species form groups: dogs and wolves, house cats and lions, zebra fish and sharks, and on and on. We now know why there are such groups: Forms related through an evolutionary lineage almost always resemble one another more than they do other evolutionary lineages. Since Linnaeus, biologists have recognized that species can be grouped into hierarchical assemblages, but they have not always understood why. Charles Darwin, and his nifty theory of evolution, answered that particular why. Darwin referred to a classification based on evolutionary history as a natural system and explained why the Linnaean system had been so successful for categorizing animals and plants: They had been placed into the hierarchical groups of the Linnaean classification on the basis of similarities, and because these similarities reflected the evolutionary closeness of the respective species, the classification tended to reflect their historical relationships. Thus, the various taxonomic categories—the families, orders, and so on—could be understood as nested, or hierarchical, models of evolution. Lines of descent link these units: All species placed in any higher category share an ancestor. Species are grouped into genera, genera into families, families into orders, orders into classes, classes into phyla, and phyla into kingdoms. The kingdoms, until recently, were the highest level.

The methodology for illustrating how the various genealogies unfolded through time was the construction of what are known as phylogenetic trees, and because of the importance that they play later, the method should be described in some detail.

A tree is a very useful analogy for understanding evolution. A tree starts from a seed, grows roots (down) and a trunk (up), and then builds an ever more anastomozing series of branches out of the trunk. In evolutionary trees the branching pattern (often called branching order) shows the genealogy of the organisms, indicating which species share more common ancestries than others. While trees help understand the lineages of things, they are poor at illustrating the relative taxonomic level of things; there is no a priori reason that one part of our tree is a kingdom, and one a class. Assigning these categories is subjective.

Linnaeus and Darwin never foresaw that humans would one day head into space—or build alien life in a test tube—and therefore saw no need for any taxonomic category higher than kingdom. The earliest practitioners of this system first recognized only two kingdoms, animals and plants, and the system worked superbly for these larger creatures. But once microbial life became accessible to biologists with their ever more sophisticated microscopes, classification became more difficult, and the number of recognized kingdoms had to increase. Bacteria appear as three simple morphologies—rods, balls, and spirals—and hence, with so little morphology to deal with, were fairly impervious to classification based on morphology. They were relegated to their own kingdom, the Monera. As biologists better understood various plantlike groups, they increased the number of kingdoms to five—the animals, plants, fungi, protozoa, and bacteria—and this classification held until the late twentieth century. But with the advent of a new system of classifying organisms, using a sophisticated method of comparing genetic codes among various microbes (and other organisms as well), a whole new view of things, a true revolution in our understanding of life's order, appeared, using genotype instead of phenotype to track evolution. The revolution was possible because of the new and powerful methods of decoding genetic sequences and codes that became standard practice for evolutionists from the late 1960s into the 1970s. The methods, ever more powerful, are still very much used, and in a way they have made all other ways of classifying obsolete, unfortunately having the effect of limiting progress in thinking about life that is not Terroan since the dominant method relies on looking at the RNA in small organelles. But heresy! What if there was a life-form on Earth—or Mars, for example—that did not have DNA? I believe that we have reached that impasse. I think that I can show that such life currently lives on Earth. How could we classify such life? *Using current procedures, we cannot!*

So what is the party line? One of the now-standard techniques for comparing microbes at the molecular level, called DNA-DNA hybridization, takes DNA from one species of microbe and mixes it with the DNA from a second species. The similarity of the DNAs (hence the similarity of the two species) is reflected in the extent to which strands of DNA from one organism anneal with strands from the other. The problem with this method is that it works best for closely related species but is much less useful in distantly related species. In such cases, a much more useful method is to study phylogenies (the actual evolutionary pathways) by comparing the similarity and differences of the molecules making up a specific gene or protein that is common to both organisms. To be useful, the target molecule must be large enough to allow comparisons. One of the most useful of such molecules, found in all Terroans, is ribosomal RNA (the transfer molecule that DNA sends off to instruct the ribosomes in protein formation). By comparing the observed RNA sequences (or those of any other appropriate molecule), one can estimate both the historical branching order of the species and the total amount of sequence change.

While many workers in the early 1970s gradually began to use this new method, it was the microbiologist Carl Woese who first recognized the full potential of RNA sequences as a measure of phylogenetic relatedness—at least among Terroans. He began to compare the sequences from many different microbes and thereby initiated a revolution.

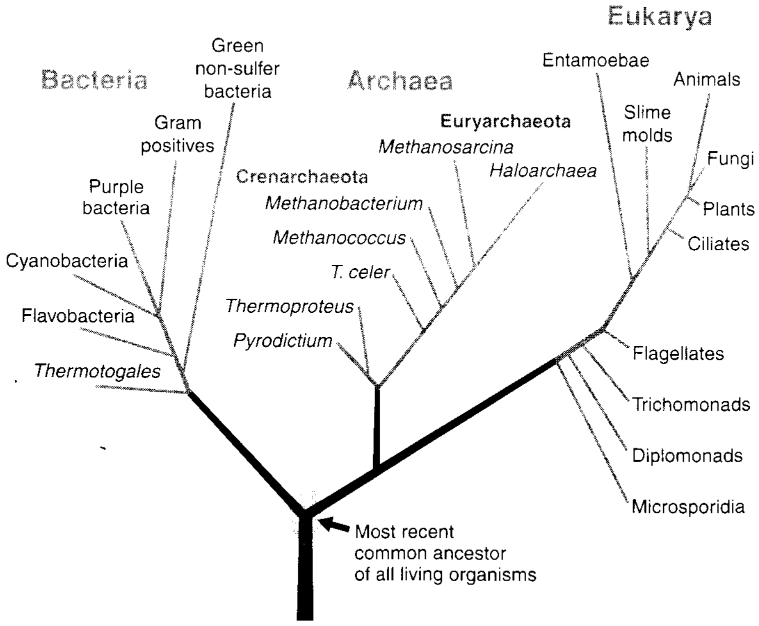
At first it would seem unlikely that the gene sequences preserved in still-living organisms could yield *any* sort of accurate key to the past, especially one of such antiquity. After all, the sequencing effort by geneticists is an attempt to unravel life's first diversification, which took place more than three billion years ago. Yet at least in some molecules, evolutionary change has been exceedingly slow. It was Woese (among others) who found that the most convenient places to study rates of evolutionary change within cells come from small subunits of RNA extracted from ribosomes; these have been the Rosetta stone, which gave a new view of Terroan evolution.

Woese was especially interested in a group of microbes called Archaeans. They had long been overlooked because they closely resemble bacteria. But once he was able to analyze their DNA by comparing their RNA sequences, it became clear that these tiny cells were as different from bacteria in genotype as bacteria are from the most primitive stocks of protozoa. This represented a huge dilemma: These differences were even greater than those found when Woese compared the RNA from the various kingdoms (animals, plants, and bacteria). Woese had discovered that the Archaeans were not even a separate kingdom; the differences were more profound. In an act of great intellectual bravery (one that had some very practical career enhancement benefits, as well as insuring his scientific immortality), Woese proposed, in 1976, that an entirely new category of life had to be erected, one that was above the level of a kingdom. He called it a domain. Using this new category, he proposed a whole new view of Terroan phylogeny.

The analysis of molecular sequences derived from living organisms, by Woese and others, thus provides a rough "map" of life's evolution as well as classifies it into groups. If portrayed in graphical form, this map becomes a "tree" like that mentioned earlier. The greater the numbers of differences between the genes, the more evolutionarily separated are the groups. It was this technique that showed the existence of the three fundamental groupings of organisms on Earth, groupings even more fundamental than the kingdoms, the domains Archaea, Bacteria, and Eukarya, and "showed" (or at least he thought that it did) that these three are the most ancient and basal branches of the tree of life still present on the planet. This analysis also showed that Bacteria and Archaea are distinct, even though both share some similarities, such as a cell without an internal nucleus. By the early 1980s the five kingdoms had became spread over the three domains: the Archaea, Bacteria, and the new category called the Eukarya, which included the old groups' plants, animals, protists, and fungi. The tree of the domains (and some of the kingdoms) is shown here, and it has come to be known as the tree of life.

The tree of life is really a model of life's evolution into the major categories of existing organisms. Various studies that compared gene sequences in various taxa gave a theoretical map of the evolutionary history of early life on Earth that first began to appear at about the same time as the discovery of the hydrothermal vents. According to these studies, there is nothing more "primitive" still living on Earth than Archaeans. They seem to show more characteristics and genes with the supposed primordial organism (the hypothesized common ancestor of all life) than any other living organism on Earth.

Much of this work contradicted long-held beliefs about the phylogeny of earth life with DNA. It showed that the division between the Bacteria and the Archaea is extremely ancient. Another surprise is the discovery that the Eukarya, the group from which higher animals and plants ultimately arose, is also extremely ancient. But by far the most intriguing result is that the most ancient of Archaeans and Bacteria are heat-loving microbes that are described as extremophiles, life that loves the extreme. In this case, the extreme they love is heat. These are just the types of microbes we find in extreme environments on Earth today. The discovery indicates that the earliest life on Earth was some sort of extremophile, suggesting that life may have first arisen on Earth under conditions of high temperature and pressure, either underwater or deep in the earth's crust, rather than in Darwin's pond, whose organisms would not have needed genes that supported life at high temperatures.



Traditional tree of earth life

A new view of the tree of life

The tree of life is a hypothesis of evolutionary pathways as well as a means of classifying life. One of the key controversies has been the placement of the "root" of the tree, the point that tells us where the most primitive organisms lie. As the tree of life is composed of three domains, the Archaea, Bacteria, and Eukarya, it is a fair question to ask: Which came first? The currently accepted view is that the Archaeans came first and then gave rise to Bacteria and finally to Eukaryans. Lateral gene transfer, in which packets of genes jumped from group to group, was integral in this early evolution.

Over the last several pages I have been informally using the term *Terroan* for life as we know it. Earth life can be defined as follows: "Heredity is preserved in nucleic acids, proteins are made in ribosomes, the same set of amino acids is used to construct proteins, energy is stored in ATP, and an almost identical genetic code is used." Here I propose to formalize this concept by placing earth life within a wholly new category of life, which sits above domain. There are now sound reasons to justify this rather bold act. And let me do this here, in this book, making it at one and the same time a science book for the public and a science book for the scientists.

Here I define a new category and place a new group within it.

***Name of new taxonomic category:* Dominion**
Definition. *A dominion is a taxonomic category that is above the level of domain and is thus composed of domains.*

Now I will formally name a dominion. The publication of this book formalizes it, according the rules and conventions of the Code of Taxonomic Practice.

> ***Dominion Terroa*, Ward, 2005**
> (*From the Latin,* earth life).
> ***Definition:*** *Life containing two-stranded DNA and utilizing it as its genome/information storage molecule; proteins made up of twenty amino acids (for specific amino acids), which are coded for by three-letter nucleotide sequences (for specific code); with a phospholipid membrane and water used as solvent in the cell.*
>
> At this time the Dominion Terroa contains three domains: *Archaea, Bacteria, and Eukarya.*

This done, we can now think about life that does not belong on this tree. And we can go looking for the non-Terroans. It turns out that we do not have to look very far. In just about any sneeze we fill whole rooms with aliens, if we define any life that is not currently on the Terroan tree of life as an alien. In chapter 1 I made the case that viruses are alive. If that is true, they have to be put on our tree of life somewhere. But where? To deal with them, we have to look at them in more detail.

What are viruses?

As we saw in chapter 1, a virus is a small bit of either DNA or RNA (its genome) packaged in a protein coat, known as the virion. To make a virus, we thus need nucleic acid of one kind or another and protein. The nucleic acid has to have some pretty complex instructions: how to break into a cell and then how to hijack its manufacturing machinery to make new viruses. Since both these products are difficult to make, the formation of the first virus is itself a perplexing problem in biosynthesis. But for a very long time, in spite of their obvious and interesting properties of parasitism, viruses were not fit subjects of study for any "frontline" biologist unless the biologist in question was interested in disease. Viruses were of no interest for their own sake. The viruses have been very clever at staying out of science's way. Because they contain no ribosomal RNA, the great tool pioneered and used by Woese and others to construct the tree of life (which is based on the differences in the sequences found in ribosomal RNA), viruses could not be compared with cellular life. Indeed, the prejudice that viruses were not alive only added to their neglect. Thus some very interesting problems, such as their origin, diversity, and ubiquity, have been overlooked. But recently this trend has changed, and viruses are getting new scrutiny. Amazing things are being discovered; some are very relevant to understanding the nature of life as we know it, as well as life as we don't. But first, let's look at viruses in general, and especially the new information about their ubiquity and diversity.

How many viruses?

The first thing that is apparent about viruses is that there are lots of them out there, and lots of different kinds. First, the how many. New research shows that viruses are almost unbelievably abundant, especially in the sea. While many microbiologists, on the basis of their realization of the staggering number of microbes found in almost any substrate or medium with any liquid at all (as well as some without, such as ice and rock), have rightly pointed out that we are in an age of bacteria, it has been estimated that there are from *one to two orders of magnitude more viruses* than there are bacteria. This is a staggering number. If we could make all the water disappear in the sea, for instance, we would see this ghost world entirely forged of viruses. They are found from the bottom of the sea (and well below the bottom of the sea) to the highest regions of the atmosphere and in every kind of life that has been examined. In one milliliter of seawater (about the volume of the tip of your thumb) there can be ten million viruses. As virologist Dennis Bamford has so unsettlingly described, "cellular life is bathing in a virtual sea of viruses," and he finishes this sentence with an even more chilling yet thought-provoking phrase:

"possibly creating the highest selective pressure they [we] encounter." What? Viruses affect evolution or perhaps channel evolution? There is an enormous importance in this last pronouncement, if true. That viruses might be of more importance in terms of adaptive pressure and natural selection than any other factor encountered by a cellular organism—more than food, habitat, predators, competition, and finding mates—seems at first glance ludicrous. Viruses, it turns out, partially compose all other life-forms. They also pervade the external biosphere and are capable of entering living cells—all living cells, it seems, with varying ease. It is as if they had the key to the tiny fortresses or castles that we call cells. They apparently have a master key or know the back-door tunnels that have been long forgotten by the cell's defenses whose job it is to guard against invasion by those that would enter and plunder. It is as if viruses were around while the first castles were being built or, more explicitly, as if they were among the original builders. There may be enormous implications to this that relate to the origin of life. What if viruses were as ubiquitous 3.7 billion years ago on Earth, when life was just beginning? There would surely not have been as many types, because much of the diversity of viruses today relates to specific hosts, and before the evolution of the first living cells there were no hosts—or were there? What if viruses preceded the evolution of cells? We will return to this thought below.

So if there are a lot of them out there, how many different ones are recognized today? Virologists have long been interested only in those that cause disease, but this has been changing recently, and many new types are discovered each day. Today the International Committee on Taxonomy of Viruses (ICTV), the ruling body of those studying the diversity of viruses, recognizes more than fifteen hundred "species" of viruses, but this number is ludicrously low. Virologists have identified another thirty thousand "strains" of distinct viruses, and this number must be a huge underestimate of what is out there. The reality is that we have a very poor idea of the diversity of Bacteria, Archaea, and Eukarya, and we know that each of these domains is riddled with parasitic viruses—perhaps millions of different kinds, in fact.

What is clear is that the great difference in the biology of a virus and a cell has made a mockery of utilizing normal taxonomic practice on viruses. A species is usually defined as a group of individuals that are reproductively viable. But viruses do not reproduce in the same way that cells do, let alone have sex of any kind. Defining a virus as a specific kind of species is probably a great disservice to the concept of species. Viral taxonomy, in fact, has been characterized as an opinionated use of data. Nevertheless, taxonomy of viruses is moving along at an accelerating rate as the result of the large amount of sequence information coming from many labs looking at the nucleic acids in various virus taxa. (Unfortunately, these are not the same sequencing practices used to differentiate Terroan life—ribosomal RNA.) The Linnaean taxonomic structure has now been applied to them, but with a few interesting additions.

The primary characters used to classify viruses are actually few in number. They include the type and organization of the viral genome. Is it RNA or DNA, and what kind of each? Second, how does the virus in question replicate? Finally, what are the morphology and chemistry of its body wall or coating like? Viral species are discriminated on the relatedness of the genome (based on sequencing), the natural host, the type of cell within the host that it normally invades, and its danger to the host, known as its pathogenicity; its mode of transmission; and the chemical properties of its virion, among other things. Once we start organizing viruses in this way, we start seeing a huge variety of forms.

Another way of looking at viruses is through their hosts. For our purposes, we can ask where on the tree of life viruses project and if specific viruses are found on only specific parts of the tree. This latter statement seems ludicrous at first. Viruses are parasites, and all cellular parasites are host-specific. We might thus expect that specific virus groups would be found on very specific branches of the tree of life. A viral type that infects mammals, for instance, would not be expected to infect a bacterium. But is this true?

We can best answer this question by first looking at the large-scale divisions of viruses, using the criteria listed earlier. The biggest distinction between viral kinds is those with DNA and those with RNA; this breaks up the viral world into two major hemispheres. After that, however, there are many other ways of subdividing the diversity of known viruses, and rather than burden this narrative with a long list of viral types, we can perhaps best do this job by summarizing the viral types and their characteristics in a table (see Table 2, p. 54).

Another unusual aspect of this new view of viruses is how they evolve. There seems to be a schizophrenic aspect to being a virus. Individual viruses specialized for parasitism of one or a few kinds of cells must constantly evolve to keep up with the defenses of the host cell. Earlier we quoted the statement that the swarms of viruses around and in each cell of life on our planet causes a huge selective pressure on the living cells. Natural selection will thus cause the cell being attacked to try new methods of defense against the viruses if they are too destructive. This type of coevolution between predator and prey, or parasite and prey, is well known. But the viruses seem to show another kind of evolution, one distinct from this day-to-day battle with the host. The virus carries two types of structural and functional components: one necessary for the day to day, and the second, far more conservative aspect of "self": the way the genome is packaged, things that go back to a long-ago time when viruses first evolved. Bamford thinks that these observations indicate that viruses and cellular life are intimately and anciently linked. He has proposed that viruses form lineages that extend from the root of the tree of life to all branches of the tree. The implication is that viruses were there when cellular life formed. This leads to a further interesting question: Were viruses opportunistic forms that early on took advantage of the earliest cellular life, riding through time as parasites, or might they have had an even more intimate acquaintance with the Terroans—in fact, as an agent in the formation of life as we know it? There is a final aspect about viruses made explicit by Bamford. At the conclusion of his article he states: "If the above reasoning is considered it follows that there is a separation between the viral and cellular world. . . . Perhaps we should consider formally dividing life into viral and cellular, where the cellular one is formed of the current domains and the viral world of its lineages." Later in the same paragraph Bamford states: "The idea of virus lineages would also mean the viruses were present before the separation of the domains of life at the very root of the tree of cellular life." Amen to that.

I encountered this sentence after I had already decided to put viruses on the tree of life and was much heartened to find a similar point of view from one who knows viruses professionally and intimately, the result of a life of study. There are enormous implications from all this about what life is, how we classify it, how we understand its evolution. There are clearly two vastly different kinds of life on Earth: viral life and cellular life. From this we must again change the tree of life that we have been building so far. And from this we can propose a new hypothesis for how life evolved.

Was the origin of virus life mono- or polyphyletic? Is there a LUVA, a last universal viral ancestor, analogous to the LUCA of cellular life?

The evolution of viruses

There are a variety of viruses on the planet today. While it has long been assumed that viruses have a single origin, there is an emerging consensus that they are polyphyletic, that they came from independent sources. This is the view I favor. Some viruses might be degenerate RNA organisms, and thus are very ancient, while others might be a more recent parasitic form.

Viruses can store their genetic information in six different types of nucleic acid which are named on the basis of how that nucleic acid eventually becomes transcribed to the viral mRNA capable of binding to host cell ribosomes and being translated into viral proteins.

In the table (+) and (–) represent complementary strands of nucleic acid. Copying of a (+) strand by complementary base pair forms a (–) strand. Only a (+) viral mRNA strand can be translated into viral protein. These six forms of viral nucleic acid are:

Type of Genome	Description	Group of Viruses
(+/–) Double-stranded DNA	The (–) DNA strand is directly transcribed into viral mRNA.	Most bacteriophages, papovaviruses, adenoviruses, herpesviruses
(+) DNA or (–) DNA	Once inside the host cell, it's converted into dsDNA, and the (–) DNA strand is transcribed into viral mRNA.	Phage M13, parvoviruses
(+/–) Double-stranded RNA	The (+) of the (+/–) RNA functions as viral mRNA.	Reoviruses
(–) RNA	The (–) RNA is copied into a (+) RNA that functions as viral mRNA.	Orthomyxoviruses paramyxoviruses, rhabdoviruses
(+) RNA	A (+) RNA is copied into (–) RNA that is transcribed into viral mRNA.	Picornaviruses, togaviruses, coronaviruses
(+) RNA	The (+) RNA is reverse transcribed into (–) DNA that makes a complementary copy to become (+/–) DNA. The (–) DNA is transcribed into viral mRNA.	Retroviruses

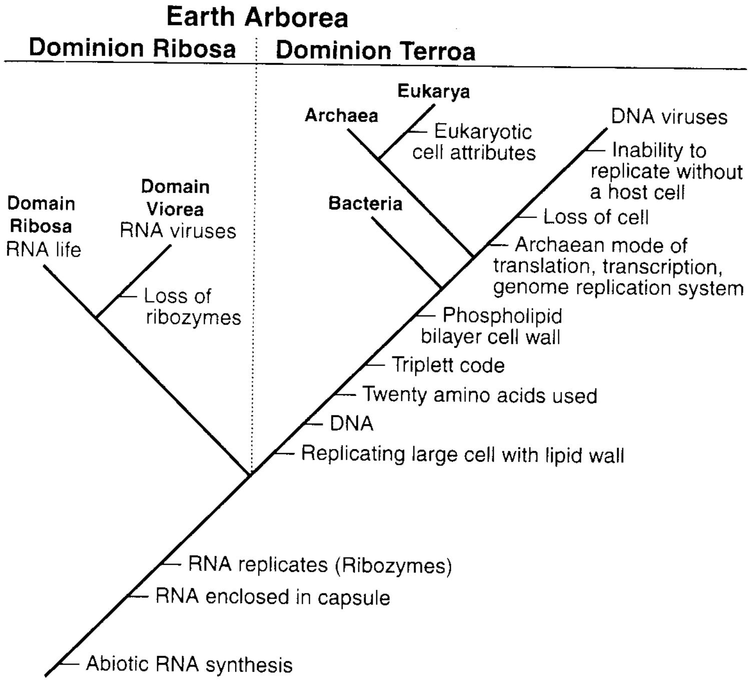
Table 2. *The Variety of Viruses and Their Specific Kinds of Genetic Code*

If all these many kinds of viruses are alive, where do they fit on our tree? They are certainly not like us Terroans as I have defined us. But they are related to us. Some kinds of viruses may actually be "living fossils" coming down through time from a period before life on Earth had DNA. These are RNA viruses. As long as twenty years ago RNA viruses were considered living fossils from that time.

So living viruses present us with a classification problem. We need to define a new taxon. Like our Terroans, it must be placed at a level higher than that currently in use. We need to define a second dominion.

So let us get that over with. Just as earlier, we can formally define this new dominion here and then get back to our cooking.

***Dominion Ribosa,* Ward, 2005**
Definition: *Life composed of carbon chemistry with water solvent with RNA as its genome.*
***Included groups:* Domain Ribovira, Ward, 2005**
Definition of Domain: Encapsulated life with RNA as genome. Includes RNA viruses.



A new hypothesis for the evolution and classification of earth life.

It is not only viruses that should be considered as living. In chapter 4 I describe the numerous reasons that suggest that some sort of RNA life preceded our familiar Terroans. An organism using RNA as its genome would not fall onto the Terroan tree. While all attention has been focused on how this perhaps mythical beast brought about the eventual evolution of us Terroans, no one has yet classified it among the current categories of earth life for the simple reason that it cannot be included in any traditional category. Suddenly we are confronted with the need to define a new group of life, one that cannot be placed within any category of earth life. So here we come to the another conclusion of this book (so far): A second domain in Ribosa of life must be identified, if RNA life existed.

> ***Domain Ribogenoma,* Ward, 2005**
> ***Definition of Domain:*** Cellular life with RNA as genome, extinct, although it is possible that extant species still exist on Earth.

Defining this group will prove very controversial, and were scientists likely to band in private clubs, this definition would get me excluded from many. Most workers in this field are very passionate about the taxonomy of life (and their favorite group), and there will be many who just hate the thought of anyone overturning the heavily burdened apple cart. Besides, there is a well-established hierarchy in this field full of Nobel laureates, and astrobiologists coming from left field with such a radical (but necessary and correct!) proposal should be vigorously snubbed. However, I believe that there are very good reasons to make this proposal, and much scientific precedent, to include both these groups in this newly defined taxonomy of earth life.

Alternatives to earth life

To this point we have looked long and hard at what life is and at what earth life is. As we have seen, life on Earth has been very successful in colonizing much of planet's surface, even down a kilometer or two into its crust, as well as far up into the atmosphere. The range of conditions goes from hot to cold. But even this great range of temperature, pressure, and amount of oxygen, acidity, and other factors influencing life are not as extreme as we find elsewhere in the solar system. Only a tiny fraction of earth life might be able to exist on many planets and moons of our solar system. But what of nonearth life? In the next chapter we'll look at what life might be in terms of chemical diversity.