WHAT

Lynn Margulis and Dorion Sagan

IS

Foreword by Niles Eldredge

LIFE?

LYNN MARGULIS
DORION SAGAN

WHAT IS LIFE?

FOREWORD BY
NILES ELDREDGE

A Peter N. Nevraumont Book

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Foreword

UNDREAMT PHILOSOPHIES

Why has evolution crafted a sentient species? Why did our consciousness, our realization of our very existence, evolve? What purpose does it serve? I am persuaded by behaviorist Nicholas Humphries's conjecture that, in being able to consult their inner selves, our ancestors gained insight on the minds of their mates, offspring, and other members of their social bands. Knowing thyself is the best way to knowing others, and thus an advantage in negotiating the complexities of daily social life.

We humans are, of course, animals. I have long thought that the very best insight into what it means to be a living, breathing animal is simply to consider one's very own life. However far our cognitive, cultural capacities have taken us from traditional existence within local ecosystems, we nonetheless still obtain energy and food to develop, grow, and maintain our corporeal existence. Many of us (perhaps too many of us) also engage in reproduction. As Lynn Margulis and Dorion Sagan tell us in *What Is Life?*, the business of maintaining corporeal existence and reproducing are quintessential activities, the very hallmarks of life. To know oneself as an organism, then, is to establish quite a few of the very basics of all living systems.

But humans, of course, do not constitute the entire biological universe. We are but one species of tens of millions now inhabiting planet Earth. And so we cannot expect to divine all of life's mysteries, all the different nuances of what it means to be alive, simply by consulting our inner selves. There are inherent limits to the revelatory principle of knowing thyself in order to know the world. But even I, a seasoned practitioner in evolutionary biology, was not fully prepared for the wild spectrum of life presented to us by Margulis and Sagan in *What Is Life?* For in these pages we meet organisms vastly different from ourselves. And we encounter ways of thinking about life that could not possibly arise from simple introspection.

What Is Life? is a feast of biological and intellectual diversity. Here we meet microbes—microscopic organisms—for which oxygen is a poison, and others who "breathe" sulfur compounds. And still others which feed on hydrogen and carbon dioxide using neither the energy from sunlight, nor that from the flesh of others. We encounter bacteria routinely exchanging genetic materials with other species—even after billions of years of evolutionary separation. We see the entire outer rind of Earth portrayed in convincing fashion as a single, mega-living system. And we learn that the evolutionary process that has produced this prodigious array has done so in astonishing ways—melding separate, simple organisms more than once to produce more complex descendant species. And therein lies a particularly interesting saga of intellectual sleuthing and derring-do.

Darwin taught us that all of life is descended from a single common ancestor. In *What Is Life?* Margulis and Sagan tell us the amazing fact that not only are our own mammalian, nucleated ("eukaryotic") cells descended from ancient bacteria, they are literally amalgams of several different strains of bacteria. Amazing! Stranger than fiction! And undreamt of in traditional biological philosophies—until Lynn Margulis began her research a quarter of a century ago.

Lynn Margulis has achieved what every scientist dreams of, but few are destined to accomplish: she has rewritten the basic textbooks. She conceived of a logical, yet audacious explanation of an outstanding fact. Human cells, like those of all animals, the eucalyptus tree and the mushroom, have most, but not all, of their DNA corralled into a cellular nucleus, neatly walled off from the various organelles that dot the plains of their typical cell's cytoplasm. It was the "not all" that attracted her attention: some of these extra-nuclear organelles—specifically, the power plants of all animal and plant cells, the "mitochondria"—were also known to have their own DNA. In plants, both mitochondria and chloroplasts, the locus of photosynthesis, have their own DNA complements. The simple question she faced was: why? Why is there an independent set of genes in these cytoplasmic organelles, when all of the "normal" genetic material is otherwise organized as double sets of chromosomes within the bounds of the nuclear walls?

Biological structures are signals of ancient evolutionary events. We owe the five fingers on our hands not to novel evolutionary events a million years ago on the African savannas, but rather to the original complement of five digits on the forefoot of the earliest land vertebrates ("tetrapods"), who evolved some 370 million years ago.

So, too, is mitochondrial DNA a holdover, a signal of an evolutionary event. But this was like no other event ever proposed in evolutionary annals: Lynn Margulis, to her everlasting credit, saw that separate DNA complements imply the fusion of at least two different kinds of other organisms, each with its own DNA complement, to form a single, complex "eukaryotic" cell. Initially condemned as heresy, this elegant idea had so much going for it that the biological world has long since accepted it. There is simply no other plausible explanation for the existence of separate DNA complements in a "single" cell.

In *What Is Life?* Lynn Margulis and Dorion Sagan tell us precisely which kinds of bacteria fused to form the original nucleated cells—*our* cells. But that is far from all, for the Margulis mind, ever restless, has kept on pushing the envelope. *What Is Life?* presents the case for an even earlier evolutionary fusion of bacteria species. Margulis has come to be convinced that such symbiotic origins of novel life forms ("symbiogenesis") has been far more common than ever dreamt by evolutionary biologists steeped in the Darwinian tradition—a tradition that emphasizes competition far more than cooperation in the evolutionary process. Symbiogenesis is Margulis's central contribution to the evolutionary dialogue, which has become enriched through her efforts to see the grand implications latent in the history of the microbial world.

But there is more to the Margulis-Sagan canon than even these profoundly new, and heretofore undreamt, philosophies. Tireless champions of the microbial world, the authors have labored mightily in an almost public-relations sense, striving to reveal the immensely diverse array of microorganisms. For microbes will not only inherit the earth (should, for example, we complex multicellular creatures fall prey to the next spasm of mass extinction); microbes got here long before we did, and in a very real sense they already "own," and most certainly run, the global system. They fix and recycle nitrogen and carbon and other essential elements otherwise unavailable to our bodies; they produce oxygen, natural gas (methane), and so on and on. Without the microbial world, life as we ourselves experience it simply could not be.

All of which lifts the Margulis gaze from the microscopic to the global: Earth truly is a living system, a globally pulsing amalgam of organisms and the physical "inanimate" world. Whether or not one chooses to call this system "Gaia" and pronounce it as alive as any organism does not, in a profound sense, really matter. For in reading *What Is Life?* we see, clearly and simply, that the global system linking life with the physical realm truly does exist, and that we humans, despite appearances and protestations to the contrary, are still very much a part of that system.

Which takes us back to the ultimate value of being aware of our own existence. As we read *What Is Life?*, we think about life's riotous diversity and evolution's exuberance, and we realize that the global system, all that life, and, in the end, *our* very own existence, are very much under threat—from our very own selves. *What Is Life?* combines the stranger-than-fiction realities of the living world with the kind of intellectual force that can reveal new undreamt philosophies. It yields the understanding we so desperately need if we are to confront the mounting threat we humans pose to the global ecosystem as we cross over the millennial divide. Knowledge is power, and *What Is Life?* equips us with an understanding of the living world that we so desperately need if we—along with the world's ecosystems—are to survive.

Niles Eldredge
American Museum of Natural History

1 LIFE: THE ETERNAL ENIGMA

Life is something edible, lovable, or lethal.

JAMES E. LOVELOCK

Life is not a thing or a fluid any more than heat is. What we observe are some unusual sets of objects separated from the rest of the world by certain peculiar properties such as growth, reproduction, and special ways of handling energy. These objects we elect to call "living things."

ROBERT MORISON

IN THE SPIRIT OF SCHRÖDINGER

Half a century ago, before the discovery of DNA, the Austrian physicist and philosopher Erwin Schrödinger inspired a generation of scientists by rephrasing for them the timeless philosophical question: *What Is Life?* (fig. 1). In his classic 1944 book bearing that title, Schrödinger argued that, despite our "obvious inability" to define it, life would eventually be accounted for by physics and chemistry. Life, Schrödinger held, is matter which, like a crystal—a strange, "aperiodic crystal"—repeats its structure as it grows. But life is far more fascinating and unpredictable than any crystallizing mineral:

> The difference in structure is of the same kind as that between an ordinary wallpaper in which the same pattern is repeated again and again in regular periodicity and a masterpiece of embroidery, say a Raphael tapestry, which shows no dull repetition, but an elaborate, coherent, meaningful design traced by the great master.[1]

FIGURE 1. Erwin Schrödinger: a physicist whose emphasis on the physiochemical nature of life helped inspire the discovery of DNA and the molecular biological revolution.

Schrödinger, a Nobel laureate, revered life in all its marvelous complexity. Indeed, although he devised the wave equation that helped give quantum mechanics theory a firm mathematical basis, he never conceived of life as simply a mechanical phenomenon.

Our book, addressing life's fullness without sacrificing any science, reproduces not only Schrödinger's title but also, we hope, his spirit. We have tried to put the life back into biology.

What is life? is surely one of the oldest questions. We live. We—people, birds, flowering plants, even algae glowing in the ocean at night—differ from steel, rocks, inanimate matter.

We are alive. But what does it mean to live, to be alive, to be a discrete being at once part of the universe but separated from it by our skin? What is life?

Thomas Mann (1875–1955) gave an admirable, if literary, answer in the novel *The Magic Mountain:*

> What was life? No one knew. It was undoubtedly aware of itself, so soon as it was life; but it did not know what it was . . . it was not matter and it was not spirit, but something between the two, a phenomenon conveyed by matter, like the rainbow on the waterfall, and like the flame. Yet why not material?—it was sentient to the point of de-

> sire and disgust, the shamelessness of matter become sensible of itself, the incontinent form of being. It was a secret and ardent stirring in the frozen chastity of the universal; it was a stolen and voluptuous impurity of sucking and secreting; an exhalation of carbonic gas and material impurities of mysterious origin and composition.[2]

Our ancestors found spirits and gods everywhere, animating all of nature. Not only were the trees alive but so was the wind howling across the savanna. Plato, in his dialogue *Laws,* said that those perfect beings, the planets, travel around Earth voluntarily in circles. Medieval Europeans believed the microcosm, the small world of the person, mirrored the macrocosm, the universe; both were part matter and part spirit. This ancient view lingers in the animals of the zodiac and in the astrological notion that celestial bodies influence mundane ones.

In the seventeenth century the German astrologer-astronomer Johannes Kepler (1571–1630) calculated that planets including Earth travel around the sun in ellipses. Nevertheless, Kepler (who wrote the first work of science fiction and whose mother was arrested as a witch) believed that the stars inhabit a three-kilometer-thick shell far beyond the solar system. He considered Earth a breathing, remembering, habit-forming monster. Although Kepler's view of a living Earth now seems whimsical, he reminds us that science is asymptotic: it never arrives at but only approaches the tantalizing goal of final knowledge. Astrology gives way to astronomy; alchemy evolves into chemistry. The science of one age becomes the mythology of the next. How will future thinkers assess our own ideas? This movement of thought—of living beings questioning themselves and their surroundings—is at the heart of the ancient question of what it means to be alive.

Life—from bacterium to biosphere—maintains by making more of itself. We focus on self-maintenance in our first chapter. Next, in chapter 2, we trace views of life from very early on through European mind-body dualism and then to modern scientific materialism. Chapter 3 explores life's origins and its memory-like preservation of the past. Our ancestors—the bacteria that brought Earth's surface to life—are featured in chapter 4.

Through symbiotic mergers, bacteria evolved into the protists of chapter 5. Protists are unicells, including algae, amebas, ciliates, and other postbacterial cells with erotic habits anticipating our own; they evolved into multicelled beings experiencing sex and death. We call the unicellular protists, together with their close multicellular relatives—some of which are very large—protoctists. The bacteria that formed protoctists were to have a spectacular future. They became animals (chapter 6), fungi (chapter 7), and plants (chapter 8). In the last chapter we pursue the unorthodox but commonsensical idea that life—not just human life but all life—is free to act and has played an unexpectedly large part in its own evolution.

LIFE'S BODY

Life, although material, is inextricable from the behavior of the living. Defying definition—a word that means "to fix or mark the limits of"—living cells move and expand incessantly. They overgrow their boundaries; one becomes two become many. Although exchanging a great variety of materials and communicating a huge quantity of information, all living beings ultimately share a common past.

Perhaps even more than Schrödinger's "aperiodic crystal," life resembles a fractal—a design repeated at larger or smaller scales. Fractals, beautiful for their delicacy and surprising in their apparent complexity, are produced by computers, as graphics programs iterate, or repeat, a single mathematical operation thousands of times. The "fractals" of life are cells, arrangements of cells, many-celled organisms, communities of organisms, and ecosystems of communities. Repeated millions of times over thousands of millions of years, the processes of life have led to the wonderful, three-dimensional patterns seen in organisms, hives, cities, and planetary life as a whole.

Life's body is a veneer of growing and self-interacting matter encasing Earth. Twenty kilometers thick, its top is the atmosphere and its bottom is continental rock and ocean depths. Life's body is like a tree trunk. Only its outermost tissues grow. Unless protected by technology, itself an extension of life, any individual removed from the living sphere is doomed.

Life, as far as is known, is limited to the surface of this third planet from the sun. Moreover, living matter utterly depends on this sun, a medium-sized star in the outback of the Milky Way Galaxy. Less than one percent of the solar energy that strikes Earth is diverted to living processes. But what life does with that one percent is astounding. Fabricating genes and offspring from water, solar energy, and air, festive yet dangerous forms mingle and diverge, transform and pollute, slaughter and nurture, threaten and overcome. Meanwhile, the biosphere itself, subtly changing with the comings and goings of individual species, lives on as it has for more than 3,000 million years.

ANIMISM VS. MECHANISM

If you wish to, you can reach for a glass of water or snap this book shut. From the experience of willing our bodies to move came animism: the view that winds come and go, rivers flow, and celestial bodies guard the heavens because something inside each wills the movement. In animism all things, not only animals, are seen to be inhabited by an inner, animating spirit. Formalized in polytheistic religion, the multiplicity of gods—a moon god, Earth god, sun god, wind god, and so on—was replaced in Islam, Judaism, and Christianity by a single god who crafted the world. Winds and rivers and celestial bodies lost their will, but living organisms—especially humans—retained theirs.

Finally, the last outposts of animism—living organisms—yielded to the philosophy of mechanism. Motion need not imply any inner consciousness; the program could have been "built in" by a creator. Wind-up toys and automated models of the solar system suggested to their inventors that even living things may be constructible from lifeless mechanisms, subtle concealed springs, tiny unseen pulleys, levers, cogs, and gears. Comparing flowing blood to a hydraulic system, the heart to a pump, English physician William Harvey (1578–1647) discovered circulation of the blood. Scientists sleuthed out the world's secret mechanisms, part of an overall design. Natural history revealed the world to be a giant mechanism made according to the mind of an omnipresent, omnipotent god.

Isaac Newton (1642–1727) became the high priest of mechanism. A devoted student of alchemy, scripture, and the occult, Newton made unparalleled innovations in optics, physics, and mathematics. In doing so he helped bridge the gap from the medieval cosmos to the modern one. Explaining the motions of the planets with a new law of gravity, Newton's equations showed that the world of the heavens and that of Earth were one and the same; the force that kept the moon in orbit was also the force that thuds an apple to the ground. So revealing were Newton's discoveries of "laws" governing the entire universe that to some it seemed he had—in Kepler's words—"glimpsed the mind of God." Inspired by Newton's analyses, Pierre-Simon de Laplace (1749–1827) speculated that, with sufficient information, the entire future of the universe, even the most minute human action, could be predicted. Far from being moved by hidden spirits, the celestial bodies now seemed to be under the governance of preexistent mathematical laws. Divine intervention became increasingly superfluous. God did not need to fiddle with creation. He had crafted it to last. The cosmos worked itself.

With a grasp of gravitation's cosmic sweep, scientists were spurred to explore phenomena once considered beyond human comprehension. Electricity and magnetism, sound and colors, radiation and heat, explosion and chemical change were all described with an eye to their underlying unity. Optical instruments, telescope and microscope, presented formerly unseen worlds of the very far and the very near. Experiment and criticism replaced blind acceptance of classical authority and divinely revealed truth. Scientists coaxed nature to yield some of her most private secrets. Oxygen's role in fire, lightning as electrical discharge, gravity as the invisible force causing the tides and attracting the moon into Earth's orbit—one by one nature laid down her cards.

Under the spell of the mechanical worldview, the ancient alchemical dream of shaping nature to human will became technological reality. After centuries of humans meddling with steamy concoctions in a Faustian quest to be godlike, then a 1953 discovery seemed to reveal the very secret of life. Life was chemical and the material basis of heredity was DNA, whose helical and staircase-like structure made clear how molecules copied themselves. Indeed, the "aperiodic crystal" that Schrödinger had predicted was uncannily similar to the double helix first described by the English chemist Francis Crick and American whiz kid James D. Watson. Replication was no longer beholden to a mysterious "vital principle"; it was the straightforward result of interacting molecules. The description of how DNA fabricated a copy of itself out of ordinary carbon, nitrogen, and phosphorus atoms was perhaps the most spectacular of all mechanism's successes. But paradoxically, this success born of self-directed minds seemed to portray life—including the scientists themselves—as the result of atoms involuntarily interacting according to changeless and inviolable chemical law.

Between these two extremes—the entire universe as alive, and the living organism as chemical and physical machine—lies the panorama of opinion. But is there not something wrong with both the mechanization of life *and* the vitalization of matter?

The world as a vast machine fails to account for our own self-awareness and self-determination because the mechanical worldview denies choice. Mechanisms, after all, don't act; they react. And mechanisms, moreover, don't come into existence on their own. The assumption that the universe is a mechanism implies that it was made according to some humanlike design—that is, by some living creator. In other words, successful as it is, the scientific mechanistic worldview is deeply metaphysical; it is rooted in religious assumptions.

The animistic view of the cosmos as a huge organism is also flawed. It blurs the distinctions among what is living, what is dead, and what has never been alive. If everything were alive, there would be no interest in—and scientists never would have discovered the replicative chemistry of—life.

We thus reject mechanism as naive and animism as unscientific. Even so, life, as an emergent behavior of matter and energy, is best known by science. Schrödinger was correct in advocating a search for the physicochemical underpinnings of life. So are Watson and Crick and other physicists and molecular biologists who hail the structure of DNA as a key to life's secrets. Like an uncoiling spring pushing the soft gears of life, DNA copies itself as it directs the making of proteins that together form the leopard's spots, the spruce tree's cone, and living bodies in general. Understanding how DNA works may be the greatest scientific breakthrough in history. Nonetheless, neither DNA nor any other kind of molecule can, by itself, explain life.

JANUS AMONG THE CENTAURS

The American architect R. Buckminster Fuller (1895–1983) applied "synergy" (from Greek *synergos,* working together) to describe entities that behave as more than the sum of their parts. From a scientific standpoint, life, love, and behavior appear to be synergistic phenomena. When certain chemicals—in water and in oil—came together long ago, life was the result. Synergy also fits the emergence of protist cells from bacteria, and of animals from such cells.

The common view is that life evolves by random genetic change that is, moreover, detrimental more often than not. Chance mutations, blind and undirected, are touted as the leading source of evolutionary novelty. We (and a growing contingent of like-minded students of life) do not entirely agree. Great gaps in evolution have been leaped by symbiotic incorporation of previously refined components—components that have been honed in separate lineages. Evolution doesn't start anew each time a new life form appears. Preexisting modules, which turn out to be primarily bacteria, already generated by mutation and retained by natural selection, come together and interface. They form alliances, mergers, new organisms, whole new complexes that act and are acted on by natural selection.

But natural selection by itself cannot generate any evolutionary innovation, as Charles Darwin (1809–1892) was well aware. Natural selection, rather, relentlessly preserves the former refinements and newly generated novelty by culling those less able to live or reproduce. Biotic potential—life's tendency to reproduce as much as possible—takes care of the rest. But first, novelty must arise from somewhere. In synergy two distinct forms come together to make a surprising new third one.

Cowboys, for example, settled the American West. Some native Americans perceived the human-horse invaders as centaurs—two-headed, multilimbed beings. The novelist and philosopher Arthur Koestler (1905–1983) has called the coexistence of smaller beings in larger wholes "holarchy."[3] Most people, by contrast, think that life on Earth is hierarchical, a great chain of being with humans on top. Koestler's coinage is free of implications of "higher" or of one of the constituents in the holarchy somehow controlling the others. The constituents, too, were given a new name by Koestler. Not merely parts, they are "holons"—wholes that also function as parts.

In his metaphysical as well as terminological rethinking, Koestler invoked the double-faced Janus, who in Roman mythology was the god of portals and the patron of beginnings and endings. In our view, just as Janus simultaneously looks backward and forward, so humans are not at the height of creation but point dually to the smaller realm of cells and the larger domain of biosphere. Life on Earth is not a created hierarchy but an emergent holarchy arisen from the self-induced synergy of combination, interfacing, and recombination.

BLUE JEWEL

The best part of a journey can be returning. By sending monkeys and cats into orbit, people to the moon, and robots to Venus and Mars, humankind has developed a new respect for, and a deeper understanding of, life on Earth.

In 1961 the Soviet Union's *Vostok I* carried the first human into orbit around Earth. Since then, gazing "down" at this turquoise orb—venturing out on a spacewalk as if about to jump from the world's highest diving board—cosmonauts and astronauts have groped for words that do justice to their experience. Eugene A. Cernan, an astronaut of both the Gemini and Apollo lunar missions, and the last person to walk on the moon, describes the view:

> When you are in Earth orbit looking down you see lakes, rivers, peninsulas. . . . You quickly fly over changes in topography, like the snow-covered mountains or deserts or tropical belts—all very visible. You pass through a sunrise and sunset every ninety minutes. When you leave Earth orbit . . . you can see from pole to pole and ocean to ocean without even turning your head. . . . You literally see North and South America go around the corner as Earth turns on an axis you can't see and then miraculously Australia, then Asia, then all of America comes to replace them. . . . You begin to see how little we understand of time. . . . You ask yourself, where am I in space and time? You watch the sun set over America and rise again over Australia. You look back "home" . . . and don't see the barriers of color, religion, and politics that divide up this world.[4]

Imagine yourself in orbit. As you circle the planet every ninety minutes, time and space undergoes a mutual metamorphosis. Gravity lessens; north and south become relative. Day follows night in a patchwork blend. The sun cuts through the thin ribbon that is the atmosphere, flooding the cabin of the spacecraft with red to green to purple, through all the colors of the rainbow. You are plunged into black. Earth becomes the place where there are no stars. If Earth can be seen at all it is as a flicker of tiny lights—cities—on the surface of the sun-eclipsing globe. "Day" breaks again, revealing the cloud-flecked blue ocean. As you are jettisoned into hyperperspective, the sky is now below. As if floating dreamily away from your own body, you watch the planet to which you are now tied by only the invisible umbilical cord of gravity and telecommunication.

The act of viewing Earth from space echoes that of a baby glimpsing, and really seeing, itself in a mirror for the first time. The astronaut gazes upon the body of life as a whole. The French psychoanalyst Jacques Lacan posits a stage in human development called "the mirror stage."[5] The infant, unable to control its limbs, looks into the mirror and perceives its whole body. Humanity's jubilant perception of the global environment represents the mirror stage of our entire species. For the first time we have caught a glimpse of our full, planetary form. We are coming to realize that we are part of a global holarchy that transcends our individual skins and even humanity as a whole.

Television images in 1969 revealed astronauts bounding over the lunar dust. The moon, once a synonym for the unattainable, was reached. A cratered wasteland, bone-dry, the moon was nevertheless still daunting in its lifelessness. As the cosmic perspective was broadcast, we homebodies were given a futuristic ride and were offered a new view of the world, a new worldview with the power to rally Earth's peoples around an icon more potent than any flag. Members of disparate religious and spiritual traditions could now join together as citizens of Earth. Individuals so affected, those who saw the potential, came to know that the whole former understanding of life was parochial, a result of where we lived. Even time was upset: night became shadow.

Tribal conflicts, national politics, and the colored geographic regions of maps are invisible from space. Science has, of course, revealed to us that this blue jewel orbits but a lackluster star in the outskirts of a spiral galaxy with myriad stars within a universe of myriad galaxies. All our history and civilization has transpired under the gaseous blanket of, really, a middling planet in one solar system. Voyaging in space, we saw Earth as home. But it is more than home: it is part of us. In contrast with the pale moon in the dead solar system of our galactic suburbs, this third planet from the sun, our Earth, is a blue-and-white flecked orb that looks alive.

IS THERE LIFE ON MARS?

Unexpectedly, the search for life on Mars provided scientific confirmation of the "body" of life as a whole on Earth. The Viking mission, launched in 1975, sent two orbiters and two landers to Mars. Although returning spectacular images of "Marscapes," the Viking landers performed a series of experiments that failed to find any evidence of Martian life. Channels carved by ancient rivers were seen, fueling hopes that evidence for past life may yet be found on the red planet.

One scientist, however, was able to search for life on Mars before the Viking mission was launched. In 1967 James E. Lovelock, English inventor of a device that measures chlorofluorocarbons implicated in the production of ozone holes, was consulted by the National Aeronautics and Space Administration (NASA) in its search for extraterrestrial life. NASA was interested in what Lovelock's invention, a gas-measuring instrument some thousand times more sensitive to certain atmospheric constituents than any previous device, might reveal about Mars. An atmospheric chemist, Lovelock suspected that, in principle, life on any planet could be detected by the chemical markers left in that planet's air. Because the constituents of Mars's atmosphere were already known by the spectroscopic signature of the planet's reflected light, Lovelock believed the data already sufficient to determine whether Mars was a living planet. His conclusion: Mars was devoid of life. Indeed, he boasted with his own brand of quiet iconoclastic mischief that his prediction precluded any need to visit Mars at all and that he could save NASA a prodigious sum of money.

Lovelock had measured Earth's atmospheric gases with a chromatograph outfitted with his new supersensitive "electron capture device." He was startled: the chemistry of Earth's atmosphere, not at all like the atmospheres of Mars and Venus, was utterly improbable. He found that methane, the chief constituent of natural gas and present in the atmospheres of the four giant planets (Jupiter, Saturn, Uranus, and Neptune), freely coexisted in Earth's atmosphere with oxygen at concentrations more than 10^{35} times higher than expected.

Methane exists at only one to two parts per million in Earth's atmosphere, but even that minuscule proportion is far too high. Methane (one carbon atom surrounded by four hydrogen atoms) and oxygen gas (two oxygen atoms) react explosively with each other to generate heat, producing carbon dioxide and water. Oxygen, the second most abundant gas in the atmosphere, should thus react immediately with methane to make the latter undetectable. Perhaps in the next minute you will die of asphyxiation because all the oxygen atoms will gather in one corner of the room and your brain will be deprived of its absolute requirement for oxygen gas. Such a calamity is improbable to the point of absurdity. Yet the chemical mixture of methane and oxygen in the Earth's air is equally freakish. Indeed, not only methane but many other gases in our air should not be detectable, given standard rules of chemical mixing. Given their tendency to react with oxygen, some of our atmosphere's components—methane, ammonia, sulfur gases, methyl chloride, and methyl iodide—are far from chemical equilibrium. Carbon monoxide, nitrogen, and nitrous oxide are respectively ten, ten thousand million, and ten trillion times more abundant than chemistry alone can account for.

Biology, however, offers an answer. Lovelock realized, for instance, that methane-producing bacteria release this gas in globally significant amounts. Cows contribute methane by belching. Belched methane does react with oxygen but, before it disappears, more is produced. The methane is made from grass by bacteria and protists in the cow's rumen, a special stomach.

Life has made our atmosphere chemically reactive and orderly, while exporting heat and disorder to space. Lovelock maintained that the atmosphere is as highly ordered as a painted tortoise's shell or a sand castle on a deserted beach. And life's inveterate ordering has left its traces on other planets. On 20 July 1976 a lander was left on Mars by the 3.6-metric-ton *Viking I* spacecraft. Although not what scientists were looking for, this machine, sitting 571 million kilometers away at Chryse Planitia on red sand, is the best, and so far the only evidence of life on Mars: solar-system exploring, technological human life.

LIFE AS VERB

Lovelock's analyses have pushed biologists to realize that life is not confined to the things now called organisms. Self-transforming, holarchic life "breaks out" into new forms that incorporate formerly self-sufficient individuals as integral parts of greater identities. The largest of these levels is the planetary layer, the biosphere itself. Each level reveals a different kind of "organic being." This is the term that Darwin used throughout his opus, *On the Origin of Species*. ("Organism," like "scientist" and "biology," had not yet been coined.) "Organic being" merits resurrection as it affords the recognition that a "cell" and the "biosphere" are no less alive than an "organism."

Life—both locally, as animal, plant, and microbe bodies, and globally, as the biosphere—is a most intricate material phenomenon. Life shows the usual chemical and physical properties of matter, but with a twist. Beach sand is usually silicon dioxide. So are the innards of a mainframe computer—but a computer isn't a pile of sand. Life is distinguished not by its chemical constituents but by the behavior of its chemicals. The question "What is life?" is thus a linguistic trap. To answer according to the rules of grammar, we must supply a noun, a thing. But life on Earth is more like a verb. It repairs, maintains, re-creates, and outdoes itself.

This surge of activity, which not only applies to cells and animals but to Earth's entire atmosphere, is intimately connected to two of science's most famous laws—the laws of thermodynamics. The first law says that throughout any transformation the total energy of any system and its environment is neither lost nor gained. Energy—whether as light, movement, radiation, heat, radioactivity, chemical or other—is conserved.

But not all forms of energy are equal; not all have the same effect. Heat is the kind of energy to which other forms tend to convert, and heat tends to disorganize matter. The second law of thermodynamics says that physical systems tend to lose heat to their surroundings.

The second law was conceived during the Industrial Revolution, when the steam engine represented the state-of-the-art in engineering. French physicist Nicolas Carnot (1796–1832), aiming to improve the efficiency of the steam engine (whose governor mechanism was invented by James Watt [1736–1819]), came to realize that heat was associated with the movement of minute particles. And from that, he envisioned the principle that is now known as the second law: In any moving or energy-using system entropy increases.

In systems undergoing change, such as steam engines or electric motors, a certain amount of the total energy available is already in, and more is converted into, a form that is unavailable for useful work. Although the amount of energy in the system and its environment stays the same (i.e., the first law of thermodynamics, of conservation of energy, holds), the amount of energy available to do work decreases. In computer science entropy is measured as the uncertainty in the information content of a message. The second law unequivocally claims that in changing systems entropy increases, implying that heat, noise, uncertainty, and other such forms of energy not useful for work, increase. As local systems lose heat, the universe as a whole is gaining it. Although not so popular now, in the past physicists and chemists have made the prediction that the universe will whimper out in a "heat death" as a consequence of the tendency for entropy to increase. More recently, they have even invented the word "negentropy" for life, which, in its tendency to increase information and certainty, seems to contradict the second law. It doesn't; the second law holds as long as one regards the system (life) in its environment.

In steam engines, coal was burned and carbon joined with oxygen, a reaction that, generating heat, made machine parts move. The leftover heat that was generated was unusable. The heat in a cabin on a snow-covered mountain seeks with seeming purpose any available crack or opening to mix with the cold air outside. Heat naturally dissipates. This dissipative behavior of heat illustrates the second law: the universe tends toward an increase in entropy, toward even temperatures everywhere, as all the energy transforms into useless heat spread so evenly that it can do no work. Heat dissipation, we are usually told, results from random particle motion. But there are other interpretations.

Some scientists have begun to interpret the second law's predilection for heat-energy as the basis for apparent purposeful action. Ilya Prigogine, a Belgian Nobel laureate, helped pioneer the consideration of life within a larger class of "dissipative structures," which also includes decidedly nonliving centers of activity like whirlpools, tornadoes, and flames.[6] A rather awkward term because it focuses on what the structures—actually, systems, not structures—throw away rather than what they retain and build, a dissipative system maintains itself, and may even grow, by importing "useful" forms of energy and exporting, or dissipating, less useful forms—notably, heat. This thermodynamic view of life actually goes back to Schrödinger, who also likened living beings to flames, "streams of order" that maintain their forms.

American scientist Rod Swenson has argued that the seeming purpose displayed in heat's tendency to dissipate with time is intimately related to the behavior of life forms striving to perpetuate themselves. In Swenson's view, this entropic universe is pocked by local regions of intense ordering, including life, because it is through ordered, dissipative systems that the rate of entropy production in the universe is maximized. The more life in the universe, the faster that various forms of energy are degraded into heat.[7]

Swenson's view shows how life's seeming purpose—its seeking behavior, its directedness, which philosophers call *teleology*—is related to the behavior of heat. Scientists do not as a rule endorse teleology. They consider it unscientific, a holdover from the primitive days of animism. Teleology is nevertheless embedded in language, and it cannot and need not be eliminated from the sciences. The prepositions "to" and "for," which build teleology—that is, purposefulness—into language, speak of a future-directedness that seems present, to some degree, in all living beings. One should not assume that only humans are future-oriented. Our own frenetic attempts, and those of the rest of life, to survive and prosper are a special, 4,000-million-year-old way the universe has organized itself "to" obey the second law of thermodynamics.

SELF-MAINTENANCE

Islands of order in an ocean of chaos, organisms are far superior to human-built machines. Unlike James Watts's steam engine, for example, the body concentrates order. It continuously self-repairs. Every five days you get a new stomach lining. You get a new liver every two months. Your skin replaces itself every six weeks. Every year, 98 percent of the atoms of your body are replaced. This nonstop chemical replacement, metabolism, is a sure sign of life. This "machine" demands continual input of chemical energy and materials (food).

Chilean biologists Humberto Maturana and Francisco Varela see in metabolism the essence of something quite fundamental to life. They call it "autopoiesis." Coming from Greek roots meaning self (*auto*) and making (*poiein,* as in "poetry"), autopoiesis refers to life's continuous production of itself.[8] Without autopoietic behavior, organic beings do not self-maintain—they are not alive.

An autopoietic entity metabolizes continuously; it perpetuates itself through chemical activity, the movement of molecules. Autopoiesis entails energy expenditure and the making of messes. Autopoiesis, indeed, is detectable by that incessant life chemistry and energy flow which is metabolism. Only cells, organisms made of cells, and biospheres made of organisms are autopoietic and can metabolize.

DNA is an unquestionably important molecule for life on Earth, but the molecule itself is not alive. DNA molecules replicate but they don't metabolize and they are not autopoietic. Replication is not nearly as fundamental a characteristic of life as is autopoiesis. Consider: the mule, offspring of a donkey and a horse, cannot "replicate." It is sterile, but it metabolizes with as much vigor as either of its parents; autopoietic, it is alive. Closer to home, humans who no longer, never can, or simply choose not to reproduce can not be relegated, by the strained tidiness of biological definition, to the realm of the nonliving. Of course, they too are alive.

In our view, viruses are not. They are not autopoietic. Too small to self-maintain, they do not metabolize. Viruses do nothing until they enter an autopoietic entity: a bacterial cell, the cell of an animal, or of another live organism. Biological viruses reproduce within their hosts in the same way that digital viruses reproduce within computers. Without an autopoietic organic being, a biological virus is a mere mixture of chemicals; without a computer, a digital virus is a mere program.

Smaller than cells, viruses lack sufficient genes and proteins to maintain themselves. The smallest cells, those of the tiniest bacteria (about one ten-millionth of a meter in diameter) are the minimal autopoietic units known today. Like language, naked DNA molecules, or computer programs, viruses mutate and evolve; but, by themselves, they are at best chemical zombies. The cell is the smallest unit of life.

When a DNA molecule produces another DNA molecule exactly like itself, we speak of replication. When living matter, as a cell or as a body made of cells, grows another similar being (with differences attributable to mutation, genetic recombination, symbiotic acquisition, developmental variation, or other factors), we speak of reproduction (see plate 2). When living matter continues to reproduce altered forms that, in turn, make altered offspring, we speak of evolution: change in populations of life forms over time. As Darwin and his legacy stress, more reproducing cells and bodies are produced by budding, cell division, hatching, birth, spore formation, and the like, than can ever survive. Those that cope long enough to reproduce are "naturally selected." Put more bluntly, it is not so much that survivors are selected for their success as that those who fail to reproduce before dying are selected against.

Identity and self-maintenance require metabolism. Metabolic chemistry (often called physiology) precedes reproduction and evolution. For a population to evolve, its members must reproduce. Yet before any organic being can reproduce, it must first self-maintain. Within the lifetime of a cell, each of five thousand or so different proteins will completely interchange with the surroundings thousands of times. Bacterial cells produce DNA and RNA (nucleic acids), enzyme proteins, fats, carbohydrates, and other complex carbon chemicals. Protoctist, fungi, animal, and plant bodies all produce these and other substances as well. But most importantly, and amazingly, any living body produces itself.

This energetic maintenance of unity while components are continuously or intermittently rearranged, destroyed and rebuilt, broken and repaired, is metabolism, and it requires energy. In accordance with the second law of thermodynamics, autopoietic self-maintenance preserves or increases internal order only by adding to the "disorder" of the external world, as wastes are excreted and heat is vented. All living beings must metabolize and therefore all must create local disorder: useless heat, noise, and uncertainty. This is autopoietic behavior, reflecting the autopoietic imperative required for any organic being that lives, that continues to function.

The autopoietic view of life differs from standard teachings in biology. Most writers of biology texts imply that an organism exists apart from its environment, and that the environment is mostly a static, nonliving backdrop. Organic beings and environment, however, interweave. Soil, for example, is not unalive. It is a mixture of broken rock, pollen, fungal filaments, ciliate cysts, bacterial spores, nematodes, and other microscopic animals and their parts. "Nature," Aristotle observed, "proceeds little by little from things lifeless to animal life in such a way that it is impossible to determine the exact line of demarcation."[9] Independence is a political, not a scientific, term.

Since life's origin, all living beings, directly or circuitously, have been connected, as their bodies and populations have grown. Interactions occur, as organisms connect via water and air. Darwin, in his *Origin of Species,* likened the complexity of these interactions to "an entangled bank"—too complex for us humans even to begin to sort out: "Throw up a handful of feathers, and all fall to the ground according to definite laws; but how simple is the problem where each shall fall compared to that of the action and reaction of the innumerable plants and animals." Yet it is the sum of these uncountable interactions that yields the largest level of life: the blue biosphere, in all the holarchic coherence and mysterious grandeur of its evolution from the black cosmos.

THE AUTOPOIETIC PLANET

The biosphere as a whole is autopoietic in the sense that it maintains itself. One of its vital "organs," the atmosphere, is clearly tended and nurtured. Earth's atmosphere, approximately one-fifth oxygen, differs radically from that of Mars and Venus. The atmospheres of these planetary neighbors are nine parts in ten carbon dioxide; in Earth's atmosphere, carbon dioxide accounts for only three parts in ten thousand. If Earth's biosphere were not made of carbon dioxide–consuming beings (plants, algae, and photosynthetic and methane-producing bacteria, among myriad other life forms), our atmosphere would long ago have reached carbon dioxide–rich chemical stability and virtually every molecule capable of reacting with another molecule would already have reacted. Instead, the combined activities of autopoietic surface life have led to an atmosphere in which oxygen has been maintained at levels of about 20 percent for at least 700 million years (fig. 2).

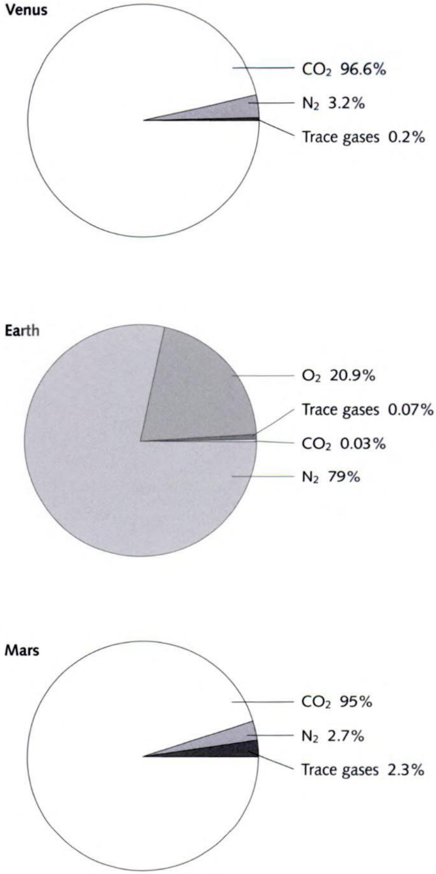

FIGURE 2. Atmospheric comparison of Earth and its two planetary neighbors. Note the comparatively high concentration of the explosive gas oxygen and the very low concentration of carbon dioxide on Earth. This atmospheric anomaly results from the incessant activity of gas-exchanging organisms. The minute physiology of the cell over geological time becomes magnified into the global physiology of the biosphere.

Other evidence for life on a planetary scale comes from astronomy. According to standard astrophysical models of the evolution of stars, the sun used to be cooler than it is now. The sun's luminosity has increased by 30 percent or more since life began on Earth. Living things can grow and reproduce only in a limited temperature range within which water is liquid. Fossils of life more than 3,000 million years old confirm that ancient temperatures were not all that dissimilar from those prevailing today; other geological evidence suggests that liquid water was widespread on Earth at least 4,000 million years ago. The increase in the luminosity of the sun should have dramatically increased the surface temperature of Earth since those early times. Because no dramatic increase has occurred—indeed, the trend may have been a cooling—it appears that the temperature of the entire biosphere has been self-maintained. By responding, life seems to have succeeded in cooling the planetary surface to counter, or more than counter, the overheating sun. Mainly by removing from the atmosphere greenhouse gases (such as methane and carbon dioxide) which trap heat, but also by changing its surface color and form (by retaining water and growing slime), life responded, prolonging its own survival.

Oceanography provides still another glimpse of the body of life as a whole. Chemical calculations suggest that salts should accumulate in the oceans to concentrations perilous to nonbacterial forms of life. Salts, such as sodium chloride and magnesium sulfate, are continuously eroded from the continents and carried into the oceans by rivers. World oceans have, however, remained hospitable to salt-sensitive organisms for at least 2,000 million years. Seafaring microorganisms may therefore be sensing and stabilizing ocean acidity and salinity levels on a global scale. How life removes salt from marine waters is obscure. Perhaps salt concentrations too high for most life are lowered, in part, by the vigorous pumping of sodium, calcium, and chloride out of cells and, in part, by formation of evaporite flats. These encrusted fields are rich in sea salt and salt-loving microbes. They often form behind lagoonal barriers made by animals such as corals or when shifting sands are trapped by the mucus and slime formed by microbial communities. Continuous desalination, if it exists, may be part of a global physiology.

Some evolutionary biologists have suggested that Earth life in its totality cannot constitute a living body, cannot be a living being, because such a body could only have evolved in competition with other bodies of the same sort—presumably, other biospheres. But, in our view, autopoiesis of the planet is the aggregate, emergent property of the many gas-trading, gene-exchanging, growing, and evolving organisms in it. As human body regulation of temperature and blood chemistry emerges from relations among the body's component cells, so planetary regulation evolved from eons of interactions among Earth's living inhabitants.

Using the energy of sunlight, only green plants, algae, and certain green- and purple-colored bacteria can convert compounds from surrounding water and air into the living stuff of their bodies. This sun-energized process, photosynthesis, is the nutritional basis for the rest of life. Animals, fungi, and most bacteria feed on the purple and green producers. Photosynthesis evolved in microbes soon after the origin of life. At every level, from microbe to planet, organic beings use air and water or other organic beings to build their reproducing selves. Local ecology becomes global ecology. As a corollary, and in spite of English grammar, life does not exist *on* Earth's surface so much as it *is* Earth's surface.

Life extends over the planet as a contiguous, but mobile, cover and takes the shape of the underlying Earth. Life, moreover, enlivens the planet; Earth, in a very real sense, is alive. This is no vague philosophical claim but rather a physiological truth of our lives. Organisms are less self-enclosed, autonomous individuals than communities of bodies exchanging matter, energy, and information with others. Each breath connects us to the rest of the biosphere, which also "breathes," albeit at a slower pace. The biosphere's breath is marked daily by increasing carbon dioxide concentrations on the dark side of the globe and decreasing concentrations on the lighted side. Annual breathing

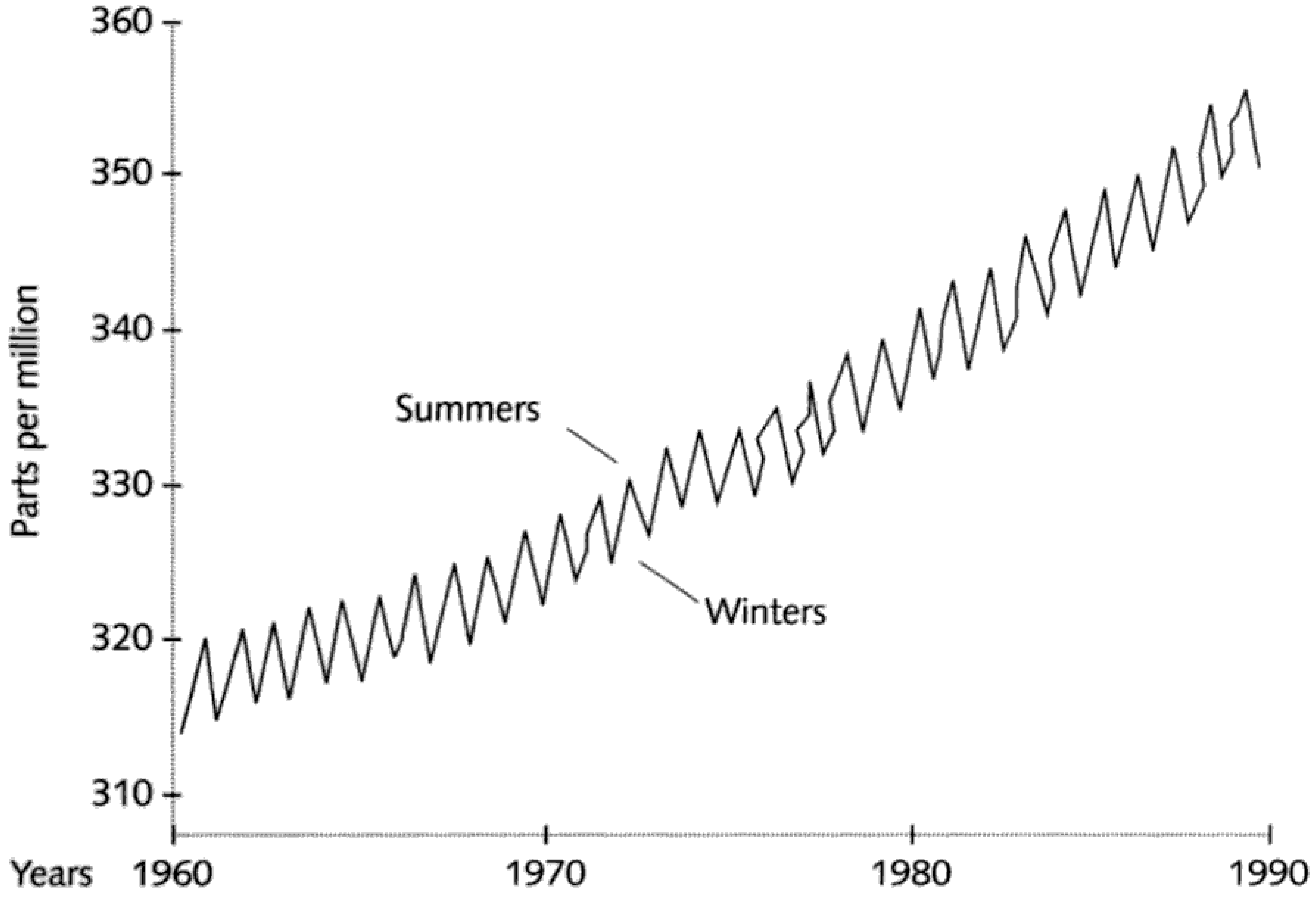

FIGURE 3. Seasonal fluctuations of carbon dioxide in the northern hemisphere. The peaks of the zigzags represent an increase in atmospheric carbon dioxide during summers; the overall upward trend indicates rising levels of CO_2 due at least in part to human activity. This seasonal and annual fluctuation of carbon dioxide in the Earth's atmosphere attests to "breathing" on a global scale. The total carbon dioxide increase may, by the greenhouse effect, raise planetary temperatures to levels inhospitable for human beings—a geophysiological "fever."

is marked by the passage of the seasons; photosynthetic activity kicks up in the northern hemisphere just as it is winding down in the south.

Taken at its greatest physiological extent, life *is* the planetary surface. Earth is no more a planet-sized chunk of rock inhabited with life than your body is a skeleton infested with cells (fig. 3).

THE STUFF OF LIFE

When German chemist Friedrich Wöhler (1800–1882) first, accidentally, produced crystals of urea by heating ammonium cyanate, he could not accept that he had made from scratch a compound so clearly associated with living beings. Urea, after all, is the carbon-nitrogenous waste produced in animal urine. And in Wöhler's day, organic beings were believed to consist of a strange and wonderful "organic matter" that was present in life—and nowhere else. Since then, dozens of carbon-rich compounds, such as formic acid, ethylene, and hydrogen cyanide, have been found not just in life but in interstellar space. The equivalent of an estimated 10 quintillion (10,000,000,000,000,000,000) fifths of whiskey, in the form of the nine-atom molecule CH_3CH_2OH (ethyl alcohol), exists in one interstellar cloud in the constellation of Orion alone.

Though adulterated with other compounds, we, like all living matter, are mostly water—that is, hydrogen and oxygen. Hydrogen forms, by mass, 75 percent of the atoms in the cosmos. It is the same element which, under intense gravitational pressure, becomes helium in the nuclear fusion reaction that makes our sun shine. Far older and bigger stars went out with a bang, as supernovas, and thereby created carbon, oxygen, nitrogen, and the other heavier elements. Life is made from such star stuff. In the universe life may be rare or even unique. But the stuff of which it is made is commonplace.

More and more inert matter, over time, has literally come to life. Minerals of the sea are now incorporated into living creatures for protection or support in the form of integument, shell, bone. Our own skeletons are built from calcium phosphate, a sea salt that was initially a nuisance or a hazard for our remote ancestors, marine protist cells which eventually found ways to cleanse their tissues by putting such minerals to use. The kinds as well as the mass of chemical elements in living bodies have increased through evolutionary time. Whereas structural compounds made of hydrogen, oxygen, sulfur, phosphorus, nitrogen, and carbon are required by all cells and have been essential to life since its inception, those made of silicon and calcium are relative newcomers.

Heinz Lowenstam (1913–1993), a Silesian-born geologist and refugee from Nazi Germany, cataloged the minerals produced in the hard parts of animals. In Lowenstam's youth, the only hard substances thought to be produced by living tissues were the calcium phosphate of our own bones and teeth, the calcium carbonate of mollusk

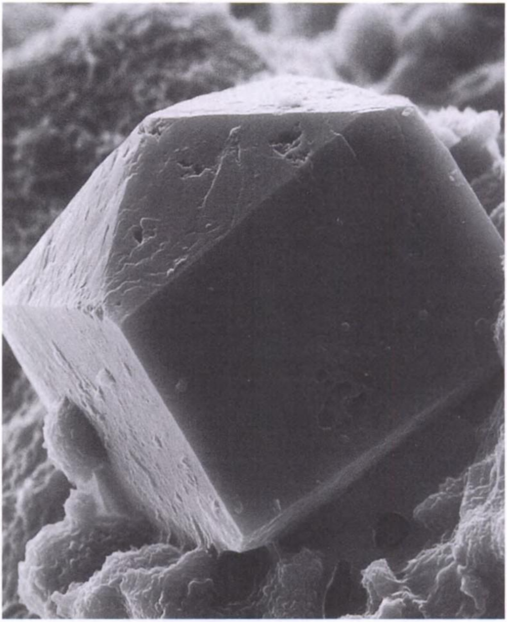

FIGURE 4. Oxalic acid crystal taken from a sea squirt renal sac, an organ thought to be a ductless kidney. *Nephromyces,* a protoctist probably associated with symbiotic bacteria, apparently forms the crystals from the animal's uric acid and calcium oxalate. Over fifty such minerals are now known to be produced in living cells.

SCIENCE / BIOLOGY / GEOLOGY

Half a century ago, before the discovery of DNA, the Austrian physicist and philosopher Erwin Schrödinger inspired a generation of scientists by reframing the fascinating philosophical question: *What is life?* Using their expansive understanding of recent science to wonderful effect, acclaimed authors Lynn Margulis and Dorion Sagan revisit this timeless question in a fast-moving, wide-ranging narrative that combines rigorous science with philosophy, history, and poetry. The authors move deftly across a dazzling array of topics—from the dynamics of the bacterial realm, to the connection between sex and death, to theories of spirit and matter. They delve into the origins of life, offering the startling suggestion that life—not just human life—is free to act and has played an unexpectedly large part in its own evolution. Transcending the various formal concepts of life, this captivating book offers a unique overview of life's history, essences, and future.

Supplementing the text are stunning illustrations that range from the smallest known organism (*Mycoplasma* bacteria) to the largest (the biosphere itself). Creatures both strange and familiar enhance the pages of *What Is Life?* Their existence prompts readers to reconsider preconceptions not only about life but also about their own part in it.

Lynn Margulis is Distinguished Professor in the Department of Geosciences at the University of Massachusetts, Amherst, and the recipient of the 1999 National Medal of Science. She is the author of more than one hundred articles and ten books, including *Symbiosis and Cell Evolution* (second edition 1993). **Dorion Sagan** is the author of *Biospheres* (1990). As partners of Sciencewriters, Margulis and Sagan have also written *Microcosmos* (California, 1996), *What Is Sex?* (1990), *Garden of Microbial Delights* (1995), *Mystery Dance* (1991), and several guides to videos of live organisms.

"In *What Is Life?* Margulis and Sagan have rephrased the answer to Schrödinger's brilliant question by means of a new and spirited explanation of the emergent levels of biological organization. . . . Theirs is a conceptual framework likely to influence future introductions to biology."
E. O. WILSON

"A witty, exuberant panorama of life that elaborates the place of symbiosis in evolution."
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