LIVING BY GAIA

Lynn Margulis

LIVING BY GAIA

by Lynn Margulis

The 2018 Cleveland conference screened a documentary film titled Symbiotic Earth: How Lynn Margulis Rocked the Boat and Started a Scientific Revolution. *NAMTA conference participants enjoyed this memorable premier event in honor of Lynn Margulis, her symbiotic worldview, and her intimate community of scientific stars. This article is taken from a series of interviews in a book titled* Talking on the Water *and is substituted for the aforementioned video.*

Reprinted from Talking on the Water: Conversations about Nature and Creativity *by Jonathan White, Trinity University Press (2016): 57-77. Reprinted with permission from the Estate of Lynn Margulis.*

Lynn Margulis' [1938–2011] resume is a single-spaced, thirty-page small-print epic. She has written over 140 scientific articles (with titles such as *Ancient Locomotion: Prokaryotic Motility Systems and Homeostatic Tendencies of the Earth's Atmosphere),* fifty reviews, and eight books. Her first book, *Origin of Eukaryotic Cells,* was published in 1970, with its third version appearing in 1993 as *Symbiosis in Cell Evolution.* Several of her recent books, including *Microcosmos, Mystery Dance: On the Evolution of Human Sexuality,* and *The Garden of Microbial Delights* (a science book for middle school students and teachers), were coauthored with Dorion Sagan, Lynn's eldest son.

Lynn was born in Chicago in 1938, the eldest of four daughters. At age fourteen, she enrolled in an undergraduate program at the University of Chicago, where she was introduced to the natural sciences. After graduating, Lynn pursued an MS in zoology and genetics at the University of Wisconsin. In 1965, she received her PhD in genetics from the University of California at Berkeley. In 1970, Lynn moved to Massachusetts where, over the following twenty-two years, she raised four children and rose through the ranks to professor at Boston University. [She was a distinguished university professor for 13 years] at the University of Massachusetts at Amherst.

Lynn is the reigning queen of the microcosmos, and especially the biological kingdom Protoctista, which includes an estimated 250,000 algae, seaweeds, amoebas, and other little-known life forms. It's here that she learned her lessons in radical scientific thinking. In the sixties she started looking for DNA where no microbiologist thought it could be found: outside the nucleus of the algal cell. She found it, and her discovery supported a revolutionary theory of symbiosis in the origin of the cell. There are four parts to the theory, three of which are now accepted in mainstream science.

The historian William Irwin Thompson once said of Lynn, "If you wish to carry on as a 'child of Gaia' or a 'healer of the planet,' one interested in getting back to nature . . . then hold on to your environmentalist virginity, cross your mind, heart, and thighs, and don't read Margulis! . . . But, if you want to understand the intricate, fundamental systems by which life creates and maintains itself, then you just might find Margulis the right place to start all over again: from the ground up."

I flew into Amherst on the crest of a December storm. Lynn has had a party the night before with over a hundred guests, celebrating the release of *Concepts of Symbiogenesis,* by Liya Nikolaevna Khakhina, which Lynn had edited with a colleague. As usual, she had several conversations going at once. Before getting started on the interview, Lynn suggested we walk down to Nancy Jane's bakery to collect a batch of fresh muffins. Roosevelt, a midsized gray mutt Lynn had rescued from the animal shelter, was anxious to join us, so we followed him out the back door. Just through the hedge, we stumbled on the garden and red-brick home of Lynn's favorite poet, Emily Dickinson. "Do you know the poem about the hummingbird? she asked, never skipping a beat. Off we went, pulled by Roosevelt and the poems and stories of a woman who, like Lynn, was a phenomenon of brilliance, energy, and love for life.

❧

Jonathan White: To get started, would you give a brief description of the Gaia hypothesis?

Lynn Margulis: The Gaia hypothesis states that certain conditions that sustain life are regulated by life itself. More specifically, the atmosphere and the sum of all life on the planet behave as a single integrated physiological system. The traditionally viewed "inert environment" is highly active, forming an integral part of the Gaian system.

The strongest evidence for Gaia comes from the study of atmospheric chemistry. The composition of the Earth's atmosphere differs radically from our nearest neighbors, Mars and Venus. Both of these planets have a carbon dioxide-rich steady-state atmosphere. The composition of their atmospheres makes perfect chemical sense. The Earth, however, is different. Loaded with reactive gases, its atmosphere makes no chemical sense whatsoever. For example, our air contains high levels of oxygen, nitrogen, and methane, among many other gases, which are violently reactive with each other. There is no way to explain this by chemistry alone. James Lovelock, the British atmospheric chemist who invented the Gaia hypothesis, puzzled over these atmospheric anomalies for a long time, concluding that the co-presence of such reactive gases are evidence that the atmospheric composition on Earth is actively regulated. The atmosphere is an extension of life. If the surface of the Earth were not covered with oxygen-emitting algae and plants, methane-producing bacteria, hydrogen-producing fermenters, and countless other life forms, its atmosphere would long ago have reached the same steady state of Mars and Venus.

Another argument for Gaia comes from astronomy. According to accepted models, our sun is 30 to 70 percent hotter today than it was in the early history of life on the planet. If the Earth's temperature were consistent with this increase in solar radiation, we would now be at a boiling point. But the temperature of the Earth has remained relatively stable and conducive to life for all this time! Some argue that this stability is just geochemical coincidence. We think that exponentially growing populations of gas-producing organisms have actively maintained surface temperatures within a range suitable for life.

JW: You're always insistent that the Gaia hypothesis is James Lovelock's, but you're often regarded as co-creator of the theory. Lovelock himself claims you were the only scientist who would talk to him about the hypothesis. When did you first meet, and how did your collaboration evolve?

LM: I met James Lovelock in 1969, but he had developed the Gaia hypothesis before then. In 1965, Jim was hired by NASA to evaluate the experiments for detecting life on Mars. In his evaluation, he and his colleague Dian Hitchcock found that the NASA experiments were inappropriate. They were designed to detect life in a place where life as we know it may not exist. "It seemed," Jim said, "that we were sent on an expedition to find camels on the Greenland ice cap, or fish among the sand dunes of the Sahara." In re-visioning the NASA experiments, Lovelock was convinced that he could use the principles of his hypothesis to detect life on Mars without ever going there. All he needed to know was the rate of gas production and removal in the atmosphere, and if these rates could be explained by physics and chemistry alone, there would be no life. If the Martian atmosphere could not be explained with physics and chemistry alone, then the chances of finding life would be much greater.

Lovelock considered calling his theory the "Biocybernetic Universal System Tendency/Homeostasis." He was talked out of this name by William Golding, author of *Lord of the Flies* and Lovelock's walking companion. What Lovelock needed, Golding said, was a good four-letter word to get the attention of his colleagues. He suggested that the theory be named after the Green goddess of the Earth, Gaia.

Meanwhile, my own work in reconstructing the history of early life on the planet was revealing that bacteria produce and remove all sorts of atmospheric gases. It was well known that plants produce oxygen, but what about the other gases? What about nitrogen oxides, hydrogen sulfide, carbon dioxide, methane, and ammonia? One or another of these gases is emitted by every lineage of bacteria I studied. I kept asking, "Why do scientists agree that oxygen is a product of life, but never discuss the thirty-five or forty other atmospheric gases? Are they a product of life too?" About six scientists with whom I talked said, "Go talk to James Lovelock. He agrees with you." And I'd say, "What do you mean he agrees with me?" I didn't pay any attention to this for a long time, but finally I wrote him. He wrote back saying he'd be coming to Massachusetts soon, so we could talk in detail then. He also wrote that, according to his calculations, the amount of methane in the Earth's atmosphere is off by an enormous factor. Given the temperatures, pressure, amount of oxygen and other gases in the atmosphere, and their known chemical reactions, there should be a virtually undetectable amount of methane. Yet methane is present in one or two parts per million everywhere. So, Lovelock asked in his letter, "Do you know of any biological process that could produce methane?" I was amused, because anybody who studies bacteria has heard of the methanogenic bacteria that live in anaerobic mud, cow rumen, and termites, among other places. They take in carbon dioxide and hydrogen and emit methane. I wrote Lovelock explaining this and he wrote again, confirming our meeting on his visit to New England. This was in 1972. And I remember the day he came to our family house in Newton, Massachusetts. When we answered the door, he said, "Hello, how are you? I answer to the name of Jim." He was very sweet and friendly. After a few minutes, he said, "You know, we've met before." And I said, "No, we haven't." "Yes," he said, "I'll tell you exactly when," and he pulled out a book called *The Origins of Life*, which I had edited in 1969. The book grew out of a very small meeting in Princeton that I had wheedled my way into because I was so fascinated by the topic. I think I was pregnant with my daughter, Jennifer, at the time. We looked at the list of attendees and, sure enough, Jim had been there. He had only spoken three sentences during the entire meeting. "Preston Cloud, the geologist, was so rude and aggressive to me," he said "that I couldn't get my ideas out. I never said a word after the introductory session."

We had a wonderful meeting, and from then on we kept up a regular correspondence. Jim sent chemical queries asking for biological processes that would account for them. He was less conversant in microbiology than I, so I helped him bring microbial awareness to his work.

It took at least two years before I understood what Jim's Gaia hypothesis really meant. In 1972 a fortuitous thing happened. Stewart Wilson of Polaroid invited Jim and me to his interactive lecture laboratory to tape a conversation on Gaia. For hours we talked back and forth. Jim asked about methane, and I'd answer by explaining how methane was produced by bacteria. He'd ask why the Earth is alkaline when our neighboring planets, Mars and Venus, are acidic. I'd suggest that ammonia, which is alkaline in water, is a common waste product of nitrogen metabolism. He asked if organisms could change the color of surface waters or sediments or if they could alter cloud coverage. He explained that the Gaia idea means that the Earth's surface is controlled and regulated by the organisms. "You mean organisms adapt to their environment?" I'd say. "No," he'd answer.

At the end of four hours of dialogue, Stewart rewound the tape so we could hear how it came out. He pushed the playback button and sat down. There was no sound, nothing. Stewart had forgotten to turn the recording switch on! "Oh my God," says Lovelock, "what are we going to do? I'm only going to be here another two days." And Stewart says, "I either have to abandon this whole project or we tape all over again." As it turns out, having to retape the session was probably the most important thing that ever happened to the early development of the Gaia hypothesis. It took two days of sessions and the time in between for me to understand something about what Lovelock was trying to say. The tape of the second dialogue served as the basis for three important papers: two technical and one popular summary that was published in the *CoEvolution Quarterly* in 1975.

JW: There are some points of the Gaia hypothesis on which you and Lovelock disagree. What are they?

LM: A recent article in *Science* magazine said, "Margulis is well known as the fervent supporter of the controversial hypothesis that the Earth is a single living organism." This kind of thing makes me angry because I never say the Earth is a single, live organism. Lovelock might, but not me. It's a bad metaphor. It leads to goddesses, mysticism, and other misconceptions about Earth. The Earth is an ecosystem, or the sum of many ecosystems. I see a big difference between a single organism and an ecosystem. For example, an organism produces gases, but it can't recycle its gaseous waste. It relies on the ecosystem for that.

JW: Lovelock likes to compare the Earth with a giant redwood tree. The interesting thing to remember, he says, is that the middle of the tree is dead wood with just a thick skin of living tissue around the circumference. Beyond that there's another dead layer, the bark, which protects the tree from the environment. Lovelock says the Earth is very much like that. You have the middle, which is molten and dead, a think skin of living tissue around the circumference, and beyond that, the atmosphere, which is just like the bark of a tree.

LM: That's an interesting comparison that helps make my point. A tree is an extraordinarily complex community. It not only includes the life you can see—the bugs and worms and birds—but also the myriad of microorganisms that live on the tree and in the soil below. What we see is a composite organism but not an ecosystem. The tree needs the rest of the ecosystem of which it is a part to deliver its carbon dioxide and water and recycle the oxygen it produces as waste. I agree that a tree is a better analogy for the Earth than a person, but there are still significant differences.

Lovelock would agree to all this, but he doesn't see a problem with using the metaphor of a living planet, particularly when speaking to the general public. He's a brilliant mischief maker, and realizes that people respond much more sympathetically to the image of a living planet than to a term like *ecosystem.* If the Earth is alive, it's harder to justify kicking it around the way we do.

Our differences are probably just a matter of how we approach the public. Lovelock is much more negative than I toward the academic establishment. He thinks academics tend to do anything to keep themselves in business. Consequently, he doesn't trust them and prefers to take his case directly to the public. I am more circumspect about this, perhaps because I work within academia. I think we're much better off if we express ourselves carefully and enlist scientists who can help develop the hypothesis. Lovelock is certainly right when he says the image of the Earth as an organism is far more moving than thinking of it as an ecosystem. But unscientific presentation alienates the very people we need most—the scientists, particularly geologists and biologists.

One of Lovelock's arguments for a life-centered metaphor is that we've lived too long with mechanistic metaphors. We think of life as a machine. We talk about the mechanisms of heredity, and we use defense analogies when we talk about fighting disease. I agree with Lovelock when he says, "What's wrong with having a living metaphor when the other metaphors are dead?" It's really just a matter of emphasis.

JW: Since the introduction of the Gaia hypothesis in 1972, both you and Lovelock have discovered that the idea is not necessarily new. Scientists such as Hutton, Lamarck, and Humbolt were emphasizing interdependence and relatedness in nature back in the eighteenth and early nineteenth centuries. Will you give a brief history of this kind of thinking?

LM: After the 1974 and 1975 publications, Jim and I started getting letters from all over the world with information about this way of thinking. We were both aware of the history of science, of course, but these letters brought to our attention a lot of unknown or previously obscure material.

James Hutton was one of the first persons to recognize that the proper study of the environment included the study of living organisms. He was a Scottish geologist, farmer, and natural philosopher who lived in the mid eighteenth century. Describing the Earth as a "superorganism," Hutton compared the churning of soil and the cycling of water between the oceans and land over time with the circulation of blood. Coming out of the age of the lifeless mechanical sciences, Hutton's view of a cyclical, organic Earth seems all the more revolutionary. He is the one who introduced the idea that life itself is a geological force, and that you can't study geology with only physics and chemistry.

The French naturalist Jean-Baptiste Lamarck, who lived about the same time as Hutton, also understood the planetary role of life, insisting on the link between geology, meteorology, chemistry, and evolutionary biology. "Living phenomena [do] not stand alone," he said, but ha[ve] to be seen as part of a larger whole, nature; indeed, they [are] only comprehensible when their constant interaction with the nonliving world [is] recognized." Lamarck is better known for his work in botany and zoology, and especially evolutionary theory, but his scientific philosophy is a precursor to our modern ecological worldview. His theories are largely rejected and trivialized to "inheritance of acquired characteristics."

Most of these early ideas are completely ignored or misconstrued. Hutton is celebrated as a geologist, but his views of "geophysiology" and the environment are all but unknown. Lamarck is passé. He gets one or two negative lines in a large college textbook of biology, and that's it. Unfortunately, much of the advancement of science has come through the last two centuries by compartmentalization. The specialized disciplines paid little or no attention to each other, much less to the unity of nature as a whole. This was particularly true of the Earth and life sciences, which ended up in separate buildings at the university, developing separate languages to address their separate fields. Lovelock calls this "academic apartheid," a phenomenon still prevalent today.

Among the few scientists opposing this fragmentation of knowledge was the German geologist Alexander von Humbolt, who lived and worked a little later than Hutton and Lamarck. He was a wonderfully dedicated scientist, working every day from the age of fourteen into old age. He was an accomplished cartographer too, and drew up plans for all kinds of weather instruments. The historian Jacques Grinvald says, "The evolution of living organisms, climate, ocean, and the Earth's crust is in fact a grand scientific idea deeply rooted in the nineteenth-century scientific world view associated in particular with Humbolt." The wide influence of Humbolt's work can be seen in early American studies of biogeography and ecology as well as in the thinking of other prominent scientists such as Charles Darwin.

The work of Vladimir Vernadsky, the most significant predecessor of these ideas, was not known to me at all until about 1978, when Stewart Brand sent me a piece of his work. I nearly flipped when I read it. With the exception of a few fragments like the piece Stewart had, none of Vernadsky's work was available in English until the very skewed publication of *The Biosphere* in 1986, an edition I cannot recommend. This was nearly fifty years later than the original French publication in 1929*, La Biosphere.* In that book, Vernadsky presents the notion of the whole Earth as an extraordinary single living phenomenon. He gives credit to the geologist Edouard Suess for having coined the term *biosphere* in 1875, but then takes the concept much further. To Vernadsky, the biosphere comprised the coevolution of "living matter" and the planetary environment of life. *Bio* means life and *sphere* means place, so *biosphere* is the sum of all life, including its environment. We owe our concept of the biosphere to Vernadsky.

In his wonderful book, *Traces of Bygone Biospheres,* A. V. Lapo says that Vernadsky's ideas were essentially unknown in the West except by G. Evelyn Hutchinson and Heinz Lowenstam. It was Vernadsky's son George, a Russian scholar at Yale, who introduced his father's ideas to the eminent ecologist Hutchinson in the last 1920s. Hutchinson was deeply impressed and helped to publish a summary of Vernadsky's work in the *American Scientist.* Ironically, the publication came out in January of 1945, just a few days after Vernadsky's death in Moscow.

The geologist Heinz Lowenstam dedicated his life's work to the study of minerals made by living processes. In the early 1940's, it was said that silica and calcium carbonate—the materials that make up animal shells and coral reefs—were the only minerals made by life. Using Vernadsky's notions of life as a geochemical force, Lowenstam showed that over fifty minerals are the result of living processes.

These are just a few of the scientists who has influence our present thinking about the Earth. As I said earlier, their contributions concerning the Earth as an integrated system that demands an interdisciplinary approach are not what you'd call mainstream ideas.

JW: The Gaia hypothesis, with its emphasis on mutualism and the reciprocity between life and the environment, appears to be a radically different view of evolution than Darwinism, which stresses natural selection through competition. Are these two theories really as incompatible as they seem?

The Gaia hypothesis, with its emphasis on mutualism and the reciprocity between life and the environment, appears to be a radically different view of evolution than Darwinism, which stresses natural selection through competition.

LM: No, they're not. Lamarck, who was really the first evolutionist, said life is connected by common ancestry through time. *Evolution* means unfolding, literally, and refers to change through time. Astronomers talk about stellar evolution when describing the changes predicted for stars, and anthropologists speak of the evolution of cultural artifacts. When we talk about organic evolution, however, we're talking about the change in living organisms over the course of Earth's history. All modern biologists agree that evolution has occurred and that organisms are related. It's when we start talking about how evolution works that we get into big trouble.

It comes down to the question of how some beings survive and leave offspring and others don't. Who or what is doing the selecting? There are surely artificial selection pressures, such as the breeding of animals by human beings. In this case, humans choose traits they like, such as cuteness or meatiness or docility, and breed animals with those traits, over and over again. But what happens when there isn't an artificial selection process? Who or what does the selecting in the natural world? Is it God? Is it the environment? Is it the biota, the sum total of life on Earth?

Darwin, who was a Lamarckian, emphasized that evolution happens by "natural selection," which has come to be understood as the "survival of the fittest." These are the prevailing Western terminologies, but even the most devout followers of Darwin admit that evolution is not a single, simple process.

An example of one aspect of this process is the potential for run-away population growth that is present in every organism. Some fungi produce one hundred thousand spores per minute. Dogs can have six or seven puppies per litter three times a year. If elephants can have four elephants, and all of them live, it wouldn't take long before the world would be completely populated with elephants. These organisms don't often realize their reproduction rate, but the potential is absolutely intrinsic to living phenomena. So why is the potential never reached? Numerous environmental factors prevent this from happening. Usually, over 99 percent of offspring die because of restrictions such as lack of food, space, water, predation, disease and so on. Darwin called these checks, and these checks are the essence of natural selection. The fact that the potential for runaway population growth is present but never fully realized is natural selection. This selecting process works on all organisms at every stage of their lives.

Up to this point, there is no contradiction between Darwinism, or even neo-Darwinism, which is the combination of Darwin's views and modern population genetics, and the Gaia hypothesis. What people miss is that it's Gaia, the ecosystem of the Earth, that keeps any given population potential in check. Life regulates life. Gaia itself does the "natural selecting." Our critics don't understand this at all. Some insist that evolution is contradictory with Gaia. The truth is, the Gaian view simply includes the environment as an evolutionary factor.

JW: Are you saying that Darwin is misinterpreted?

LM: Yes, both Darwin and Lovelock are misinterpreted. Darwin was a wonderful biologist, but he was also full of contradictions. So full of contradictions, in fact, that you can find evidence in his work to support almost anything. Although he was anthropocentric at times, he also acknowledged the ancestral connection between human beings and other mammals. He discouraged the use of judgmental terms in evolution, such as describing one form as better or higher than another. Instead, he preferred to say that one form is more suitably adapted to a particular environment than another.

One criticism of Darwin is his lack of consideration for the environment. In his view, organisms adapt to the environment as if it were some independent entity with a capital E. There is no acknowledgement whatsoever of an active, mutually constructive exchange between any given life form and its living environment. The Gaian view, which accepts this mutual exchange, does not contradict Darwin's vision but takes it a step further.

One criticism of Darwin is his lack of consideration for the environment. In his view, organisms adapt to the environment as if it were some independent entity with a capital E. There is no acknowledgement whatsoever of an active, mutually constructive exchange between any given life form and its living environment. The Gaian view, which accepts this mutual exchange, does not contradict Darwin's vision but takes it a step further.

It's no longer sufficient to study only biology in the pursuit of how evolution works. We need other sciences, especially geology and chemistry, if we're going to have any hope of understanding the whole system. The neo-Dawrinist view, which is our present paradigm for scientific thinking in the West, denies the need for chemistry, climatology, geology, comparative planetology, and the like. Instead, it promotes the capitalistic view that organisms succeed over time just because they leave the most progeny or are better at outwitting their neighbors.

JW: Richard Dawkins, author of *The Selfish Gene,* is an outspoken critic of the Gaia hypothesis. He claims that life is made up of a network of small, self-interested components. A neo-Darwinist, Dawkins says, "Entities that pay the costs of furthering the well-being of the ecosystem as a whole will tend to reproduce themselves less successfully than rivals that exploit their public-spirited colleagues, and contribute nothing to the general welfare." Along with Dawkins, other scientists such as Ford Doolittle and Stephen Jay Gould insist that regulation of the planet by the biota would require foresight and planning—a kind of global-scale altruism that could not evolve through natural selection. Because the Earth itself does not reproduce, there would be no pressure for it to evolve as "the most fit planet." How do you respond to these criticisms?

LM: Neo-Darwinism's current funk over altruism reflects a failure to comprehend that every organism is part of a larger ecosystem, a system on which it depends for respiratory gas, water, food, and a sink for waste products. Are bacteria "public spirited" in ridding themselves of their waste, which happens to be the oxygen necessary for the other organisms in the system? Are those bacteria that don't produce oxygen "cheating" and thus at a reproductive advantage? I don't think so. Dawkins's claim that the Gaia hypothesis cannot be true because there is no evidence for competition between Earth and its neighboring planets reflects a preoccupation with the romantic, Victorian conception of evolution as a prolonged and bloody battle. Life, according to the neo-Darwinists, is a collective of individuals who reproduce, mutate, and reproduce their mutations. These mutations are assumed to arise by chance. The life-centered alternative to this view recognizes that, with the exception of bacteria, individuals with single genetic systems don't exist. All other living organisms, such as animals, plants, and fungi, are complex communities of multiple, tightly organized beings. What we generally accept as an individual animal, such as a cow, is really a collection of entities that together form an "emergent domain." The hind-gut of a termite, for example, is loaded with over twenty-five different kinds of bacteria and protists. Each of these organism types evolved over millions of years to perform a role in the "domain" that we recognize as a "termite." Without them, the termite would starve to death, because it alone is unable to digest wood. Yet termites acquire their vital supply of bacteria and protists not through their genes but in a peculiar ritual of feeding on the anal fluid of their fellow termites. There are dozens of examples of this mutual reliance, or what the philosopher Gail Fleischaker would call nestedness, in nature.

In this view, organisms do not compete in the neo-Darwinian sense—"nature, red in tooth and claw"—nor are they selected by God or some other "higher intelligence." It's not the individual but the community of life that evolves by cooperation, interaction, and mutual dependence. Life did not take over the globe by combat but by networking. As the philosopher David Abram says, "The interaction of life and the environment is more a dialogue where the environment puts questions to the organism and the organism, in answering those questions, puts new questions to the environment. The environment, in turn, answer with further questions."

JW: Some argue that while the Gaia hypothesis is a good idea, promoting a much-needed shift from a human-centered to a life-centered perspective, it is not—and never will be—provable. What is the current status on the search for mechanisms that demonstrate the existence of planetary regulation?

LM: Some work is being done, but it's a slow and complicated process. A current example is the study on cloud formation and temperature regulation over the ocean. Robert Charlson, an atmospheric scientist from the University of Washington in Seattle, has found that certain marine algae produce compounds that enter the atmosphere. Once there, they serve as particles around which clouds form. In warm temperatures, the algae bloom, causing more clouds. The increasing clouds reflect the sun's light and warmth back up into the atmosphere causing cooler temperatures and fewer algae. Few algae means fewer clouds, and fewer clouds mean a rise in temperature. With that, the cycle begins again. The net result is temperature regulation. Although this is an oversimplified presentation, it's a good example of how organisms affect the environment without sitting around in a committee and deciding what or how to regulate. I've seen satellite photographs of these tiny algae on the ocean's surface that extend fifty by two hundred kilometers.

Any mechanism that's regulating life has some sort of sensor that sends a signal to an amplifier. This is part of any feedback system, whether it be Gaian or manmade. The thermostat in your home is a sensor that sends a signal to the furnace, which amplifies the signal by turning on and generating heat. In the example I just gave of cloud-temperature regulation over the ocean, light or temperature is the signal these tiny algae receive. The amplifier is the potential for runaway population growth, which we talked about earlier. With lots of light and warm temperatures, these algae grow exponentially until, as a result of their growth, their conditions change again. The new signal, generated by more clouds, is less light or cooler temperatures. Thus the cycle reverses itself. This is the essence of a positive and negative feedback system. Now what's the difference between a manmade and a Gaian system? A manmade system is modeled by an engineer; in the Gaian system, feedback is an intrinsic property of the living system itself.

I see two basic approaches to the search for natural feedback systems. The first approach uses a model that results from the observation of global phenomena, like the temperature regulation by algae that I just described. The second approach attempts to remove the living elements of a miniaturized system in order to measure the effect their absence has on the rest of the system. Schwartzman, a geologist from Howard University in Washington, used this method in his studies of weathering. Until he proved differently, the breakdown of rock was considered only a physical and chemical process, primarily involving erosion by water and wind. Nobody who studied weathering needed to know anything about biology. By removing the organisms in a miniaturized system, Schwartzman found that the rate of weathering was reduced by a factor of a thousand! This is a great example of how the Gaia hypothesis, whether it's true or not, is promoting new scientific inquiry. Because of the obvious problems of miniaturizing a system or isolating elements within it, these experiments are not done often. Biosphere projects, like Biosphere II in Arizona, are another good example of this kind of approach.

When it was first stated, the Gaia hypothesis had three parts to it: temperature regulation, chemical regulation (oxygen, nitrogen, methane, and so on), and acidity/alkalinity (pH) regulation. New research, generated by the hypothesis itself, has revealed that the regulation and distribution of heavy metals, such as gold, iron, manganese, and copper may be added to that list. Water salinity in the oceans may be regulated by Gaia, too. We know that tons of salts are deposited there each year by streams and rivers. With no mechanism for removal, the salinity of the oceans should steadily increase, yet it has remained relatively stable for over five hundred million years. Why? I'm convinced that we'll eventually discover a Gaian mechanism for salt regulation. And, in that process, my suspicion is that we'll find evidence to support the argument that life influences lateral plate movement also.

A most striking current possibility is that life may play a role in retaining water on this planet. Venus and Mars are both very dry. Why? Because the elements—principally hydrogen—that water comprises escape from the atmosphere into space. In fact, it looks like a whole ocean's worth of water has escaped from Mars and Venus! The ozone layer in our atmosphere, which is made by life, prevents the loss of water to the upper atmosphere. That's one way life might be regulating the retention of water, but there are other ways too. For example, the scum that grows over the surface of ponds and lakes helps to prevent evaporation.

Ultimately, it doesn't matter whether the hypothesis is proved or not. The fact that it has generated new thoughts and new work is the best evidence of its value. It may be that all these experiments will show that life makes no difference at all, that the surface of the Earth is run completely by nonliving properties. That's one solution. Another solution is that life determines *all* regulation. The answer, of course, is probably somewhere in between. For example, no one claims that the amounts of neon, krypton, helium, and argon in the Earth's atmosphere are regulated by life. These gases, unlike carbon, nitrogen, and hydrogen, are not reactive.

JW: In *Microcosmos,* you say that the ancestor of all life first appeared in the form of bacterial cells 3.5 billion years ago. These earliest forms of life learned almost everything there is to know about living in a system, and what they learned is, principally, what we know today. These bacteria are still with us, you say, in our DNA and in our consciousness. We are surrounded by them and composed of them. This not only challenges the way we look at ourselves as individuals, but also the way we look at time and history.

LM: The past is all around us. Darwin's biggest contribution was to show us that all individual organisms are connected through time. It doesn't matter whether you compare kangaroos, bacteria, humans, or salamanders, we all have incredible chemical similarities. As far as I know, no one disagrees with this. Vernadsky showed us that organisms are not only connected through time but also through space. The carbon dioxide we exhale as a waste product becomes the life-giving force for a plant; in turn, the oxygen waste of a plant gives us life. This exchange of gas is what the word *spirit* means. Spirituality is essentially the act of breathing. But the connection doesn't stop at the exchange of gases in the atmosphere. We are also physically connected, and you can see evidence of this everywhere you look. Think of the protists that live in the hind-gut of the termite, or the fungi that live in the rootstock of trees and plants. The birds that flitter from tree to tree transport fungi spores throughout the environment. Their droppings host a community of insects and microorganisms. When rain falls on the droppings, spores are splashed back up on the tree, creating pockets for life to begin to grow again. This interdependence is an inexorable fact of life. As Vernadsky said, without this interdependence, no organism can hope to survive.

The fact that we are connected through space and time shows that life is a unitary phenomenon, no matter how we express that fact. We are not one living organism, but we constitute a single ecosystem with many differentiated parts. I don't see this as a contradiction, because parts and wholes are nested in each other.

JW: Biologically speaking, does all this mean we're not different than our hunter-gatherer ancestors of ten thousand years ago?

LM: We're somewhat different, of course. The corn seed you plant today is not exactly the same as the one you planted last year. There are differences and similarities, both.

We think of change in qualitative, hierarchical terms. We think of life as starting from a single cell and becoming more complex until we arrive at humankind, the pinnacle of evolutionary accomplishment. Most accounts of evolution don't even begin until a few hundred million years ago. But life began long before that. Of the 3.5 billion years that life has existed on Earth, the entire history of human beings from the cave to the condominium represents less than one-tenth of 1 percent. Feeding, moving, mutating, sexually recombining, photosynthesizing, reproducing, overgrowing, predacious, and energy-expanding symbiotic microorganisms preceded all animals and all plants by at least one billion years. Our powers of intelligence and technology, then, do not belong specifically to us but to all life. As Lewis Thomas says, "For all our elegance and eloquence as a species, for all our massive frontal lobes, for all our music, we have not progressed all that far from our microbial forebears. They are still with us, part of us. Or, to put it another way, we are part of them."

Life is a continuous phenomenon. You can't point to any of the great global catastrophes, like the one that wiped out the dinosaurs during the Cretaceous period sixty-five million years ago, and say that it extinguishes *all* life. It's true that thousands of species are now extinct, and that life itself has undergone huge changes in composition and detail. But in spite of all this, life's connection through space and time remains essentially unbroken.

JW: Apparently there have been over thirty of these catastrophic events in Earth's history, all of which were thousands of times more severe than anything humans can generate, including an all-out nuclear war. If the Gaian system is not threatened by these events, doesn't that shed a new light on the movement to "save the Earth?"

LM: Absolutely. It's not the Earth that's in jeopardy, it's the middle class Western life-style. Soil erosion, loss of nutrients, methane production, ozone depletion, deforestation, and the loss of species diversity may all be Gaian processes, but surely our behavior has accentuated them to the point of near catastrophe. It's quite possible that our ecocidal environmental policies and our insidious overpopulation will stress the system to such an extent that the Earth will roll over into another steady-state regime, which may or may not include human life.

The idea that we are "stewards of the Earth" is another symptom of human arrogance. Imagine yourself with the task of overseeing your body's physiological processes. Do you understand the way it works well enough to keep all its systems in operation? Can you make your kidneys function? Can you control the removal of waste? Are you conscious of the blood flow through your arteries, or the fact that you are losing a hundred thousand skin cells a minute? We are unconscious of most of our body's processes, thank goodness, because we'd screw it up if we weren't. The human body is so complex, with so many parts, yet it is only one infinitesimally small part of the Gaian system, a system which is far more complex than we can fully imagine. The idea that we are consciously caretaking such a large and mysterious system is ludicrous.

Many things we must do are more simple and straightforward than steering the planet into the future. We must stop using plastics for packaging or throw-away products such as fishing nets and champagne cups. We must stop using paper and plastic plates and tiny bottles of shampoo. We must use more silk, which is strong and durable as well as biodegradable. We could distribute grains grown in the Midwest to countries that need them. We must vastly improve the education of our children. So many things we can do are simple and tangible, yet living in an anti-intellectual country, we seem to lack the political will.

We need to recognize that humans have a large effect on the environment but relatively little effect on any idealized planetary system. Ultimately, it's the quality of life for humankind and other large animals that we affect most profoundly by our behavior. I don't think we should feel embarrassed or ashamed to show concern for our own survival. The Earth will live on until the sun dies—it's just a question of whether we'll be a part of its future.