J. E. Lovelock, *Gaia: A New Look at Life on Earth*, Oxford University Press, 1979. Excerpts.

Introductory

As I write, two Viking spacecraft are circling our fellow planet Mars, awaiting landfall instructions from the Earth. Their mission is to search for life, or evidence of life, now or long ago. This book also is about a search for life, and the quest for Gaia is an attempt to find the largest living creature on Earth. Our journey may reveal no more than the almost infinite variety of living forms which have proliferated over the Earth's surface under the transparent case of the air and which constitute the biosphere. But if Gaia does exist, then we may find ourselves and all other living things to be parts and partners of a vast being who in her entirety has the power to maintain our planet as a fit and comfortable habitat for life.

The quest for Gaia began more than fifteen years ago, when NASA (the National Aeronautics and Space Administration of the USA) first made plans to look for life on Mars. It is therefore right and proper that this book should open with a tribute to the fantastic Martian voyage of those two mechanical Norsemen.

In the early nineteen-sixties I often visited the Jet Propulsion Laboratories of the California Institute of Technology in Pasadena, as consultant to a team, later to be led by that most able of space biologists Norman Horowitz, whose main objective was to devise ways and means of detecting life on Mars and other planets. Although my particular brief was to advise on some comparatively simple problems of instrument design, as one whose childhood was illuminated by the writings of Jules Verne and Olaf Stapledon I was delighted to have the chance of discussing at first hand the plans for investigating Mars. . . .

After a year or so, and perhaps because I was not directly involved, the euphoria arising from my association with this enthralling problem began to subside, and I found myself asking some rather down-to-earth questions, such as, 'How can we be sure that the Martian way of life, if any, will reveal itself to tests based on Earth's life style?' To say nothing of more difficult questions, such as, 'What is life, and how should it be recognised?'

Some of my still sanguine colleagues at the Jet Propulsion Laboratories mistook my growing scepticism for cynical disillusion and quite properly asked, 'Well, what would you do instead?' At that time I could only reply vaguely, 'I'd look for an entropy reduction, since this must be a general characteristic of all forms of life.' Understandably, this reply was taken to be at the best unpractical and at worst plain obfuscation, for few physical concepts can have caused as much confusion and misunderstanding as has that of entropy.

It is almost a synonym for disorder and yet, as a measure of the rate of dissipation of a system's thermal energy, it can be precisely expressed in mathematical terms. It has been the bane of generations of students and is direfully associated in many minds with decline and decay, since its expression in the Second Law of Thermodynamics (indicating that all energy will eventually dissipate into heat universally disturbed and will no longer be available for the performance of useful work) implies the predestined and inevitable run-down and death of the Universe.

Although my tentative suggestion had been rejected, the idea of looking for a reduction or reversal of entropy as a sign of life had implanted itself in my mind. It grew and waxed fruitful until, with the help of many colleagues, Dian Hitchcock, Sidney Epton, Peter Simmonds, and especially Lynn Margulis, it evolved into the hypothesis which is the subject of this book. . . .

The design of a universal life-detection experiment based on entropy reduction seemed at this time to be a somewhat unpromising exercise. However, assuming that life on any planet would be bound to use the fluid media-oceans, atmosphere, or both-as conveyor-belts for raw materials and waste products, it occurred to me that some of the activity associated with concentrated entropy reduction within a living system might spill over into the conveyor-belt regions and alter their composition. The atmosphere of a life-bearing planet would thus become recognisably different from that of a dead planet.

Mars has no oceans. If life had established itself there, it would have had to make use of the atmosphere or stagnate. Mars therefore seemed a suitable planet for a life-detection exercise based on chemical analysis of the atmosphere. Moreover, this could be carried out regardless of the choice of landing site. Most life-detection experiments are effective only within a suitable target area. Even on Earth, local search techniques would be unlikely to yield much positive evidence of life if the landfall occurred on the Antarctic ice sheet or the Sahara desert or in the middle of a salt lake.

While I was thinking on these lines, Dian Hitchcock visited the Jet Propulsion Laboratories. Her task was to compare and evaluate the logic and information-potential of the many suggestions for detecting life on Mars. The notion of life detection by atmospheric analysis appealed to her, and we began developing the idea together. Using our own planet as a model, we examined the extent to which simple knowledge of the chemical composition of the Earth's atmosphere, when coupled with such readily accessible information as the degree of solar radiation and the presence of oceans as well as land masses on the Earth's surface, could provide evidence for life.

Our results convinced us that the only feasible explanation of the Earth's highly improbable atmosphere was that it was being manipulated on a day-to-day basis from the surface, and that the manipulator was life itself. The significant decrease in entropy-or, as a chemist would put it, the persistent state of disequilibrium among the atmospheric gases-was on its own clear proof of life's activity. Take, for example, the simultaneous presence of methane and oxygen in our atmosphere. In sunlight, these two gases react chemically to give carbon dioxide and water vapour. The rate of this reaction is such that to sustain the amount of methane always present in the air, at least 1,000 million tons of this gas must be introduced into the atmosphere yearly. In addition, there must be some means of replacing the oxygen used up in oxidising methane and this requires a production of at least twice as much oxygen as methane. The quantities of both of these gases required to keep the Earth's extraordinary atmospheric mixture constant was improbable on an abiological basis by at least 100 orders of magnitude.

Here, in one comparatively simple test, was convincing evidence for life on Earth, evidence moreover which could be picked up by an infra-red telescope sited as far away as Mars. The same argument applies to other atmospheric gases, especially to the ensemble of reactive gases constituting the atmosphere as a whole. The presence of nitrous oxide and of ammonia is as anomalous as that of methane in our oxidising atmosphere. Even nitrogen in gaseous form is out of place, for with the Earth's abundant and neutral oceans, we should expect to find this element in the chemically stable form of the nitrate ion dissolved in the sea.

Our findings and conclusions were, of course, very much out of step with conventional geochemical wisdom in the mid-sixties. With some exceptions, notably Rubey, Hutchinson, Bates, and Nicolet, most geochemists regarded the atmosphere as an end-product of planetary out-gassing and held that subsequent reactions by abiological processes had determined its present state. Oxygen, for example, was thought to come solely from the breakdown of water vapour and the escape of hydrogen into space, leaving an excess of oxygen behind. Life merely borrowed gases from the atmosphere and returned them unchanged. Our contrasting view required an atmosphere which was a dynamic extension of the biosphere itself. It was not easy to find a journal prepared to publish so radical a notion but, after several rejections, we found an editor, Carl Sagan, prepared to publish it in his journal, *Icarus.*

Nevertheless, considered solely as a life-detection experiment, atmospheric analysis was, if anything, too successful. Even then, enough was known about the Martian atmosphere to suggest that it consisted mostly of carbon dioxide and showed no signs of the exotic chemistry characteristic of Earth's atmosphere. The implication that Mars was probably a lifeless planet was unwelcome news to our sponsors in space research. To make matters worse, in September 1965 the US Congress decided to abandon the first Martian exploration programme, then called Voyager. For the next year or so, ideas about looking for life on other planets were to be discouraged.

Space exploration has always served as a convenient whipping-boy to those needing money for some worthy cause, yet it is far less expensive than many a stuck-in-the-mud, down-to-earth technological failure. Unfortunately, the apologists for space science always seem over-impressed by engineering trivia and make far too much of non-stick frying pans and perfect ball-bearings. To my mind, the outstanding spin-off from space research is not new technology. The real bonus has been that for the first time in human history we have had a chance to look at the Earth from space, and the information gained from seeing from the outside our azure-green planet in all its global beauty has given rise to a whole new set of questions and answers. Similarly, thinking about life on Mars gave some of us a fresh standpoint from which to consider life on Earth and led us to formulate a new, or perhaps revive a very ancient, concept of the relationship between the Earth and its biosphere.

By great good fortune, so far as I was concerned, the nadir of the space programme coincided with an invitation from Shell Research Limited for me to consider the possible global consequences of air pollution from such causes as the ever-increasing rate of combustion of fossil fuels. This was in 1966, three years before the formation of Friends of the Earth and similar pressure-groups brought pollution problems to the forefront of the public mind. . . .

The link between my involvement in problems of global air pollution and my previous work on life detection by atmospheric analysis was, of course, the idea that the atmosphere might be an extension of the biosphere. It seemed to me that any attempt to understand the consequences of air pollution would be incomplete and probably ineffectual if the possibility of a response or an adaptation by the biosphere was overlooked. The effects of poison on a man are greatly modified by his capacity to metabolise or excrete it; and the effect of loading a biospherically controlled atmosphere with the products of fossil fuel combustion might be very different from the effect on a passive inorganic atmosphere. Adaptive changes might take place which would lessen the perturbations due, for instance, to the accumulation of carbon dioxide. Or the perturbations might trigger some compensatory change, perhaps in the climate, which would be good for the biosphere as a whole but bad for man as a species.

Working in a new intellectual environment, I was able to forget Mars and to concentrate on the Earth and the nature of its atmosphere. The result of this more single-minded approach was the development of the hypothesis that the entire range of living matter on Earth, from whales to viruses, and from oaks to algae, could be regarded as constituting a single living entity, capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts.

It is a long way from a plausible life-detection experiment to the hypothesis that the Earth's atmosphere is actively maintained and regulated by life on the surface, that is, by the biosphere. Much of this book deals with more recent evidence in support of this view. In 1967 the reasons for making the hypothetical stride were briefly these:

Life first appeared on the Earth about 3,500 million years ago. From that time until now, the presence of fossils shows that the Earth's climate has changed very little. Yet the output of heat from the sun, the surface properties of the Earth, and the composition of the atmosphere have almost certainly varied greatly over the same period.

The chemical composition of the atmosphere bears no relation to the expectations of steady-state chemical equilibrium. The presence of methane, nitrous oxide, and even nitrogen in our present oxidising atmosphere represents violation of the rules of chemistry to be measured in tens of orders of magnitude. Disequilibria on this scale suggest that the atmosphere is not merely a biological product, but more probably a biological construction: not living, but like a cat's fur, a bird's feathers, or the paper of a wasp's nest, an extension of a living system designed to maintain a chosen environment. Thus the atmospheric concentration of gases such as oxygen and ammonia is found to be kept at an optimum value from which even small departures could have disastrous consequences for life.

The climate and the chemical properties of the Earth now and throughout its history seem always to have been optimal for life. For this to have happened by chance is as unlikely as to survive unscathed a drive blindfold through rush-hour traffic.

By now a planet-sized entity, albeit hypothetical, had been born, with properties which could not be predicted from the sum of its parts. It needed a name. Fortunately the author William Golding was a fellow-villager. Without hesitation he Recommended that this creature be called Gaia, after the Greek Earth goddess also known as Ge, from which root the sciences of geography and geology derive their names. In spite of my ignorance of the classics, the suitability of this choice was obvious. It was a real four-lettered word and would thus forestall the creation of barbarous acronyms, such as Biocybernetic Universal System Tendency/Homoeostasis. I felt also that in the days of Ancient Greece the concept itself was probably a familiar aspect of life, even if not formally expressed. Scientists are usually condemned to lead urban lives, but I find that country people still living close to the earth often seem puzzled that anyone should need to make a formal proposition of anything as obvious as the Gaia hypothesis. For them it is true and always has been.

I first put forward the Gaia hypothesis at a scientific meeting about the origins of life on Earth which took place in Princeton, New Jersey, in 1969. Perhaps it was poorly presented. It certainly did not appeal to anyone except Lars Gunnar Sillen, the Swedish chemist now sadly dead, and Lynn Margulis, of Boston University, who had the task of editing our various contributions. A year later in Boston Lynn and I met again and began a most rewarding collaboration which, with her deep knowledge and insight as a life scientist, was to go far in adding substance to the wraith of Gaia, and which still happily continues.

We have since defined Gaia as a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet. The maintenance of relatively constant conditions by active control may be conveniently described by the term 'homoeostasis'.

Gaia has remained a hypothesis but, like other useful hypotheses, she has already proved her theoretical value, if not her existence, by giving rise to experimental questions and answers which were profitable exercises in themselves. If, for example, the atmosphere is, among other things, a device for conveying raw materials to and from the biosphere, it would be reasonable to assume the presence of carrier compounds for elements essential in all biological systems, for example, iodine and sulphur. It was rewarding to find evidence that both were conveyed from the oceans, where they are abundant, through the air to the land surface, where they are in short supply. The carrier compounds, methyl iodide and dimethyl sulphide respectively, are directly produced by marine life. Scientific curiosity being unquenchable, the presence of these interesting compounds in the atmosphere would no doubt have been discovered in the end and their importance discussed without the stimulus of the Gaia hypothesis. But they were actively sought as a result of the hypothesis and their presence was consistent with it.

If Gaia exists, the relationship between her and man, a dominant animal species in the complex living system, and the possibly shifting balance of power between them, are questions of obvious importance. I have discussed them in later chapters, but this book is written primarily to stimulate and entertain. The Gaia hypothesis is for those who like to walk or simply stand and stare, to wonder about the Earth and the life it bears, and to speculate about the consequences of our own presence here. It is an alternative to that pessimistic view which sees nature as a primitive force to be subdued and conquered. It is also an alternative to that equally depressing picture of our planet as a demented spaceship, forever travelling, driverless and purposeless, around an inner circle of the sun.

. . . Having assumed her existence, let us consider three of Gaia's principle characteristics which could profoundly modify our interaction with the rest of the biosphere.

1. The most important property of Gaia is the tendency to keep constant conditions for all terrestrial life. Provided that we have not seriously interfered with her state of homeostasis, this tendency should be as predominant now as it was before man's arrival on the scene.
2. Gaia has vital organs at the core, as well as expendable or redundant one's mainly on the periphery. What we do to our planet may depend greatly on where we do it.
3. Gaian responses to changes for the worse must obey the rules of cybernetics, where the time constant and the loop gain are important factors. Thus the regulation of oxygen has a time constant measured in thousands of years. Such slow processes give the least warning of undesirable trends. By the time it is realized that all is not well and action is taken, inertial drag will bring things to a worse state before an equally slow improvement can set in.

Epilogue

. . . From a Gaian viewpoint, all attempts to rationalise a subjugated biosphere with man in charge are as doomed to failure as the similar concept of benevolent colonialism. They all assume that man is the possessor of this planet; if not the owner, then the tenant. The allegory of Orwell's *Animal Farm* takes on a deeper significance when we realise that all human societies in one way or another regard the world as their farm. The Gaia hypothesis implies that the stable state of our planet includes man as a part of, or partner in, a very democratic entity.

Among several difficult concepts embodied in the Gaia hypothesis is that of intelligence. Like life itself, we can at present only categorise and cannot completely define it. Intelligence is a property of living systems and is concerned with the ability to answer questions correctly. We might add, especially questions about those responses to the environment which affect the system's survival, and the survival of the association of systems to which it belongs.

At the cellular level, decisions as to the edibility or otherwise of things encountered, and as to whether the environment is favourable or hazardous, are vital for survival. They are, however, automatic processes and do not involve conscious thought. Much of the routine operation of homoeostasis, whether it be for the cell, the animal, or for the entire biosphere, takes place automatically, and yet it must be recognised that some form of intelligence is required even within an automatic process, to interpret correctly information received about the environment. To supply the right answers to simple questions such as: 'Is it too hot?' or: 'Is there enough air to breathe?' requires intelligence. Even at the most rudimentary level, the primitive cybernetic system discussed in chapter 4, which provides the correct answer to the simple question about the internal temperature of the oven, requires a form of intelligence. Indeed, all cybernetic systems are intelligent to the extent that they must give the correct answer to at least one question. If Gaia exists, then she is without doubt intelligent in this limited sense at the least.

There is a spectrum of intelligence ranging from the most rudimentary, as in the foregoing example, to our own conscious and unconscious thoughts during the solving of a difficult problem. We saw something of the complexity of our own body-temperature regulatory system in chapter 4, although we were mainly concerned with that part which is wholly automatic and does not involve conscious action. Compared with the thermostasis of a kitchen oven, the body's automatic temperature-regulating system is intelligent to the point of genius, but it is still below the level of consciousness. It is to be compared in intelligence with the level of the regulatory mechanisms which we would expect to find Gaia using.

With creatures who possess the capacity of conscious thought and awareness, and no one as yet knows at what level of brain development this state exists, there is the additional possibility of cognitive anticipation. A tree prepares for winter by shedding its leaves and by modifying its internal chemistry to avoid damage from frost. This is all done automatically, drawing on a store of information handed down in the tree's genetic set of instructions. We on the other hand may buy warm clothes in preparation for a journey to New Zealand in July. In this we use a store of information gathered by our species as a collective unit and which is available to us all at the conscious level. So far as is known, we are the only creatures on this planet with the capacity to gather and store information and use it in this complex way. If we are a part of Gaia it becomes interesting to ask: 'To what extent is our collective intelligence also a part of Gaia? Do we as a species constitute a Gaian nervous system and a brain which can consciously anticipate environmental changes?' . . .

Still more important is the implication that the evolution of *homo sapiens*, with his technological inventiveness and his increasingly subtle communications network, has vastly increased Gaia's range of perception. She is now through us awake and aware of herself. She has seen the reflection of her fair face through the eyes of astronauts and the television cameras of orbiting spacecraft. Our sensations of wonder and pleasure, our capacity for conscious thought and speculation, our restless curiosity and drive are hers to share. This new interrelationship of Gaia with man is by no means fully established; we are not yet a truly collective species, corralled and tamed as an integral part of the biosphere, as we are as individual creatures. It may be that the destiny of mankind is to become tamed, so that the fierce, destructive, and greedy forces of tribalism and nationalism are fused into a compulsive urge to belong to the commonwealth of all creatures which constitutes Gaia. It might seem to be a surrender, but I suspect that the rewards, in the form of an increased sense of well-being and fulfilment, in knowing ourselves to be a dynamic part of a far greater entity, would be worth the loss of tribal freedom. . . .

What should we have thought of an early race of hunters who developed a taste for horsemeat and then proceeded to eliminate the horse from the Earth by systematically hunting and killing every one, merely to satisfy their appetite? Savage, lazy, stupid, selfish, and cruel are some of the epithets that come to mind; and what a waste to fail to recognise the possibility of the working partnership between horse and man! It is bad enough to cull or farm the whale so as to provide a constant supply of those products which whale-hunting nations claim are needed by their backward and primitive industries. If we hunt them heedlessly to extinction it must surely be a form of genocide, and will be an indictment of the indolent and hidebound national bureaucracies, Marxist and capitalist alike, which have neither the heart to feel nor the sense to comprehend the magnitude of the crime. Yet perhaps it is not too late for them to see the error of their ways. Perhaps one day the children we shall share with Gaia will peacefully co-operate with the great mammals of the ocean and use whale power to travel faster and faster in the mind, as horse power once carried us over the ground.