INTRODUCTION: THE MICROCOSM

WHEN people look at life on Earth, it is easy to think we are supreme. The power of consciousness, of our society and our technical inventions, has made us think we are the most advanced form of life on the planet. Even the great blackness of space seen does not humble us. We view space as a no man's land to penetrate and conquer as we believe we have conquered the Earth.

Life on Earth has traditionally been studied as a prologue to humans: "lower" forms of life lacking intelligence preceded us and we now stand at the pinnacle of evolution. Indeed, so godlike do we consider ourselves that we may think we are taking evolution into our own hands by manipulating DNA, the mainspring of life, according to our own design. We study the microcosm—the age-old world of microorganisms—to discover life's secret mechanisms so that we can take better control, perhaps even "perfect" ourselves and the other living things on the Earth.

But during the past three decades, a revolution has taken place in the life sciences. Fossil evidence of primeval microbial life, the decoding of DNA, and discoveries about the composition of our own cells have exploded established ideas about the origins of life and the dynamics of evolution on Earth.

First, they have shown the folly of considering people as special, apart and supreme. The microscope has gradually exposed the vastness of the microcosm and is now giving us a startling view of our true place in nature. It now appears that microbes—also called microorganisms, germs, bugs, protozoans, and bacteria, depending on the context—are not only the building blocks of life, but occupy and are indispensable to every known living structure on the Earth today. From the paramecium to the human race, all life forms are meticulously organized, sophisticated aggregates of evolving microbial life. Far from leaving microorganisms behind on an evolutionary "ladder," we are both surrounded by them and composed of them. Having survived in an unbroken line from the beginnings of life, all organisms today are equally evolved.

This realization sharply shows up the conceit and presumption of attempting to measure evolution by a linear progression from the simple—so-called lower—to the more complex (with humans as the absolute "highest" forms at the top of the hierarchy). As we shall see, the simplest and most ancient organisms are not only the forebears and the present substrate of the Earth's biota, but they are ready to expand and alter themselves and the rest of life, should we "higher" organisms, be so foolish as to annihilate ourselves.

Next, the view of evolution as chronic bloody competition among individuals and species, a popular distortion of Darwin's notion of "survival of the fittest," dissolves before a new view of continual cooperation, strong interaction, and mutual dependence among life forms. Life did not take over the globe by combat, but by networking. Life forms multiplied and complexified by co-opting others, not just by killing them.

Because we cannot see the microcosm with the unaided eye, we tend to discount its significance. Yet of the three-and-a-half billion years that life has existed on Earth, the entire history of human beings from the cave to the condominium represents far less than one percent. Not only did life originate on earth very early in its history as a planet, but for the first full two billion years, Earth was inhabited solely by bacteria.

In fact, so significant are bacteria and their evolution that the fundamental division in forms of life on Earth is not that between plants and animals, as is commonly assumed, but between prokaryotes—organisms composed of cells with no nucleus, that is, bacteria—and eukaryotes—all the other life forms.[1] In their first two billion years on Earth, prokaryotes continuously transformed the Earth's surface and atmosphere. They invented all of life's essential, miniaturized chemical systems—achievements that so far humanity has not approached. This ancient high *bio*technology led to the development of fermentation, photosynthesis, oxygen breathing, and the removal of nitrogen gas from the air. It also led to worldwide crises of starvation, pollution, and extinction long before the dawn of larger forms of life.

These staggering events early in life's history came about by the interaction of at least three recently discovered dynamics of evolution. The first is the remarkable orchestrating abilities of DNA. Identified as the heredity-transmitting substance in 1944 by Oswald T. Avery, Colin MacLeod, and

Maclyn McCarty, DNA's code was cracked in the 1960s after its method of replication was revealed by James Watson and Francis Crick in 1953. Governed by DNA, the living cell can make a copy of itself, defying death and maintaining its identity by reproducing. Yet by also being susceptible to mutation, which randomly tinkers with identity, the cell has the potential to survive change.

A second evolutionary dynamic is a sort of natural genetic engineering. Evidence for it has long been accumulating in the field of bacteriology. Over the past fifty years or so, scientists have observed that prokaryotes routinely and rapidly transfer different bits of genetic material to other individuals. Each bacterium at any given time has the use of accessory genes, visiting from sometimes very different strains, which perform functions that its own DNA may not cover. Some of the genetic bits are recombined with the cell's native genes; others are passed on again. Some visiting genetic bits can readily move into the genetic apparatus of eukaryotic cells (such as our own) as well.

These exchanges are a standard part of the prokaryotic repertoire. Yet even today, many bacteriologists do not grasp their full significance: that as a result of this ability, all the world's bacteria essentially have access to a single gene pool and hence to the adaptive mechanisms of the entire bacterial kingdom. The speed of recombination over that of mutation is superior: it could take eukaryotic organisms a million years to adjust to a change on a worldwide scale that bacteria can accommodate in a few years. By constantly and rapidly adapting to environmental conditions, the organisms of the microcosm support the entire biota, their global exchange network ultimately affecting every living plant and animal. Human beings are just learning these techniques in the science of genetic engineering, whereby biochemicals are produced by introducing foreign genes into reproducing cells. But prokaryotes have been using these "new" techniques for billions of years. The result is a planet made fertile and inhabitable for larger forms of life by a communicating and cooperating worldwide superorganism of bacteria.

Far-reaching as they are, mutation and bacterial genetic transfer alone do not account for the evolution of all the life forms on the earth today. In one of the most exciting discoveries of modern microbiology, clues to a third avenue of change appeared in the observation of mitochondria—tiny membrane-wrapped inclusions in the cells of animals, plants, fungi, and protists alike. Although they lie outside the nucleus in modern cells, mitochondria have their own genes composed of DNA. Unlike the cells in which they reside, mitochondria reproduce by simple division. Mitochondria reproduce at different times from the rest of the cell. Without mitochondria, the nucleated cell, and hence the plant or animal, cannot utilize oxygen and thus cannot live.

Subsequent speculation brought biologists to a striking scenario: The descendants of the bacteria that swam in primeval seas breathing oxygen three billion years ago exist now in our bodies as mitochondria. At one time, the ancient bacteria had combined with other microorganisms. They took up residence inside, providing waste disposal and oxygen-derived energy in return for food and shelter. The merged organisms went on to evolve into more complex oxygen-breathing forms of life. Here, then, was an evolutionary mechanism more sudden than mutation: a symbiotic alliance that becomes permanent. By creating organisms that are not simply the sum of their symbiotic parts—but something more like the sum of all the possible combinations of their parts—such alliances push developing beings into uncharted realms. Symbiosis, the merging of organisms into new collectives, proves to be a major power of change on Earth.[2]

As we examine ourselves as products of symbiosis over billions of years, the supporting evidence for our multimicrobe ancestry becomes overwhelming. Our bodies contain a veritable history of life on Earth. Our cells maintain an environment that is carbon- and hydrogen-rich, like that of the Earth when life began. They live in a medium of water and salts like the composition of the early seas. We became who we are by the coming together of bacterial partners in a watery environment. Although the evolutionary dynamics of DNA, genetic transfer, and symbiosis were not discovered until almost a century after Charles Darwin's death in 1882, he had the shrewdness to write, "We cannot fathom the marvellous complexity of an organic being; but on the hypothesis here advanced this complexity is much increased. Each living creature must be looked at as a microcosm—a little universe, formed of a host of self-propagating organisms, inconceivably minute and as numerous as the stars in heaven."[3] The strange nature of this little universe is what this book is about.

The detailed structure of our cells betrays the secrets of their ancestors. Electron microscopic images of nerve cells from all animals reveal numerous conspicuous "microtubules." The waving cilia in the lining of our throats and the whipping tail of the human sperm cell both have the same unusual "telephone dial" arrangement of microtubules as do the cilia of ciliates, a group of successful microbes including more than eight thousand different species. These same microtubules appear in all cells of plants, animals, and fungi each time the cells divide. Enigmatically, the microtubules of dividing cells are made of proteins nearly identical to some found in brain cells; and these proteins resemble those found in certain fast-moving bacteria we hypothesize were among our ancestors.

These and other living relics of once-separate individuals, detected in a variety of species, make it increasingly certain that all visible organisms evolved through symbiosis, the coming together that leads to physical interdependence and the permanent sharing of cells and bodies. Although, as we shall see, some details of the bacterial origin of microtubules, mitochondria, and other cell parts are hard to explain, the general outline of how evolution can work by symbiosis is agreed upon by those scientists who are familiar with the lifestyles of the microcosm.

The symbiotic process goes on unceasingly. We organisms of the macrocosm continue to interact with and depend upon the microcosm, as well as upon each other. Certain families of plants (such as the pea family, including peas, beans, and their relatives such as clover and vetch) cannot live in nitrogen-poor soil without the nitrogen-fixing bacteria in their root nodules, and we cannot live without the nitrogen that comes from such plants. Neither cows nor termites can digest the cellulose of grass and wood without communities of microbes in their guts. Fully ten percent of our own dry body weight consists of bacteria, some of which, although they are not a congenital part of our bodies, we can't live without. No mere quirk of nature, such coexistence is the stuff of evolution itself. Let evolution continue a few million years more, for example, and those microorganisms producing vitamin B_{12} in our intestines may become parts of our own cells. An aggregate of specialized cells may become an organ. The union of once-lethal bacteria with amoebae, creating over time a new species of hybrid amoeba, has even been witnessed in the laboratory.

This revolution in the study of the microcosm brings before us a breathtaking view. It is not preposterous to postulate that the very consciousness that enables us to probe the workings of our cells may have been born of the concerted capacities of millions of microbes that evolved symbiotically to become the human brain. Now, this consciousness has led us to tinker with DNA and we have begun to tap in to the ancient process of bacterial genetic transfer. Our ability to make new kinds of life can be seen as the newest way in which organic memory—life's recall and activation of the past in the present—becomes more acute. In one of life's giant, self-referential loops, changing DNA has led to the consciousness that enables us to change DNA. Our curiosity, our thirst to know, our enthusiasm to enter space and spread ourselves and our probes to other planets and beyond represents part of the cutting edge of life's strategies for expansion that began in the microcosm some three-and-a-half billion years ago. We are but reflections of an ancient trend.

From the first primordial bacteria to the present, myriads of symbiotically formed organisms have lived and died. But the microbial common denominator remains essentially unchanged. Our DNA is derived in an unbroken sequence from the same molecules in the earliest cells that formed at the edges of the first warm, shallow oceans. Our bodies, like those of all life, preserve the environment of an earlier Earth. We coexist with present-day microbes and harbor remnants of others, symbiotically subsumed within our cells. In this way, the microcosm lives on in us and we in it.

Some people may find this notion disturbing, unsettling. Besides popping the overblown balloon that is our presumption of human sovereignty over the rest of nature, it challenges our ideas of individuality, of uniqueness and independence. It even violates our view of ourselves as discrete physical beings separated from the rest of nature. To think of ourselves and our environment as an evolutionary mosaic of microscopic life evokes imagery of being taken over, dissolved, annihilated. Still more disturbing is the philosophical conclusion we will reach later, that the possible cybernetic control of the Earth's surface by unintelligent organisms calls into question the alleged uniqueness of human intelligent consciousness.

Paradoxically, as we magnify the microcosm to find our origins, we appreciate sharply both the triumph and the insignificance of the individual. The smallest unit of life—a single bacterial cell—is a monument of pattern and process unrivaled in the universe as we know it. Each individual that grows, doubles its size, and reproduces is a great success story. Yet just as the individual's success is subsumed in that of its species, so is the species subsumed in the global network of all life—a success of an even greater order of magnitude.

It is tempting, even for scientists, to get carried away by success stories. From the disciples of Darwin to today's genetic engineers, science has popularized the view that humans are at the top rung of Earth's evolutionary "ladder" and that with technology we have stepped outside the framework of evolution. Some eminent and sophisticated scientists, such as Francis Crick in his book, *Life Itself,* write that life in general and human consciousness in particular are so miraculous that they couldn't be earthly at all, but must have originated elsewhere in the universe.[4] Others still believe that humans are a product of a fatherly "higher intelligence"—the children of a divine patriarch.

This book was written to show that these views underestimate the Earth and the ways of nature. There is no evidence that human beings are the supreme stewards of life on Earth, nor the lesser offspring of a superintelligent extraterrestrial source. But there is evidence to show that we are recombined from powerful bacterial communities with a multibillion-year-old history. We are a part of an intricate network that comes from the original bacterial takeover of the Earth. Our powers of intelligence and technology do not belong specifically to us but to all life. Since useful attributes are rarely discarded in evolution it is likely that our powers, derived from the microcosm, will endure in the microcosm. Intelligence and technology, incubated by humankind, are really the property of the microcosm. They may well survive our species in forms of the future that lie beyond our limited imaginations.