The Future of Life by E.O. Wilson:

CHAPTER 1

TO THE ENDS OF EARTH

The totality of life, known as the biosphere to scientists and creation to theologians, is a membrane of organisms wrapped around Earth so thin it cannot be seen edgewise from a space shuttle, yet so internally complex that most species composing it remain undiscovered. The membrane is seamless. From Everest's peak to the floor of the Mariana Trench, creatures of one kind or another inhabit virtually every square inch of the planetary surface. They obey the fundamental principle of biological geography, that wherever there is liquid water, organic molecules, and an energy source, there is life. Given the near-universality of organic materials and energy of some kind or other, water is the deciding element on planet Earth. It may be no more than a transient film on grains of sand, it may never see sunlight, it may be boiling hot or supercooled, but there will be some kind of organism living in or upon it. Even if nothing alive is visible to the naked eye, single cells of microorganisms will be growing and reproducing there, or at least dormant and awaiting the arrival of liquid water to kick them back into activity.

An extreme example is the McMurdo Dry Valleys of Antarctica, whose soils are the coldest, driest, and most nutritionally deficient in the world. On first inspection the habitat seems as sterile as a cabinet of autoclaved glassware. In 1903, Robert F. Scott, the first to explore the region, wrote, "We have seen no living thing, not even a moss or lichen; all that we did find, far inland among the moraine heaps, was the skeleton of a Weddell seal, and how that came there is beyond guessing." On all of Earth the McMurdo Dry Valleys most resemble the rubbled plains of Mars.

But the trained eye, aided by a microscope, sees otherwise. In the parched streambeds live twenty species of photosynthetic bacteria, a comparable variety of mostly single-celled algae, and an array of microscopic invertebrate animals that feed on these primary producers. All depend on the summer flow of glacial and icefield meltwater for their annual spurts of growth. Because the paths of the streams change over time, some of the populations are stranded and forced to wait for years, perhaps centuries, for the renewed flush of meltwater. In the even more brutal conditions on bare land away from the stream channels live sparse assemblages of microbes and fungi together with rotifers, bear animalcules, mites, and springtails feeding on them. At the top of this rarefied food web are four species of nematode worms, each specialized to consume different species in the rest of the flora and fauna. With the mites and springtails they are also the largest of the animals, McMurdo's equivalent of elephants and tigers, yet all but invisible to the naked eye.

The McMurdo Dry Valleys's organisms are what scientists call extremophiles, species adapted to live at the edge of biological tolerance. Many populate the environmental ends of Earth, in places that seem uninhabitable to gigantic, fragile animals like ourselves. They constitute, to take a second example, the "gardens" of the Antarctic sea ice. The thick floes, which blanket millions of square miles of ocean water around the continent much of the year, seem forbiddingly hostile to life. But they are riddled with channels of slushy brine in which single-celled algae flourish year-round, assimilating the carbon dioxide, phosphates, and other nutrients that work up from the ocean below. The garden photosynthesis is driven by energy from sunlight penetrating the translucent

matrix. As the ice melts and erodes during the polar summer, the algae sink into the water below, where they are consumed by copepods and krill. These tiny crustaceans in turn are the prey of fish whose blood is kept liquid by biochemical antifreezes.

The ultimate extremophiles are certain specialized microbes, including bacteria and their superficially similar but genetically very different relatives the archaeans. (To take a necessary digression: biologists now recognize three domains of life on the basis of DNA sequences and cell structure. They are the Bacteria, which are the conventionally recognized microbes; the Archaea, the other microbes; and the Eukarya, which include the single-celled protists or "protozoans," the fungi, and all of the animals, including us. Bacteria and archaeans are more primitive than other organisms in cell structure: they lack membranes around their nuclei as well as organelles such as chloroplasts and mitochondria.) Some specialized species of bacteria and archaeans live in the walls of volcanic hydrothermal vents on the ocean floor, where they multiply in water close to or above the boiling point. A bacterium found there, *Pyrolobus fumarii*, is the reigning world champion among the hyperthermophiles, or lovers of extreme heat. It can reproduce at 235°F, does best at 221°F, and stops growing when the temperature drops to a chilly 194°F. This extraordinary feat has prompted microbiologists to inquire whether even more advanced, ultrathermophiles exist, occupying geothermal waters at 400°F or even higher. Watery environments with temperatures that hot exist. The submarine spumes close to the *Pyrolobus fumarii* bacterial colonies reach 660°F. The absolute upper limit of life as a whole, bacteria and archaeans included, is thought to be about 300°F, at which point organisms cannot sustain the integrity of DNA and the proteins on which known forms of life depend. But until the search for ultrathermophiles, as opposed to mere hyperthermophiles, is exhausted, no one can say for certain that these intrinsic limits actually exist.

During more than three billion years of evolution, the bacteria and archaeans have pushed the boundaries in other dimensions of physiological adaptation. One species, an acid lover (acidophile), flourishes in the hot sulfur springs of Yellowstone National Park. At the opposite end of the pH scale, alkaliphiles occupy carbonate-laden soda lakes around the world. Halophiles are specialized for life in saturated salt lakes and salt evaporation ponds. Others, the barophiles (pressure lovers), colonize the floor of the deepest reaches of the ocean. In 1996, Japanese scientists used a small unmanned submersible to retrieve bottom mud from the Challenger Deep of the Mariana Trench, which at 35,750 feet is the lowest point of the world's oceans. In the samples they discovered hundreds of species of bacteria, archaeans, and fungi. Transferred to the laboratory, some of the bacteria were able to grow at the pressure found in the Challenger Deep, which is a thousand times greater than that near the ocean surface.

The outer reach of physiological resilience of any kind may have been attained by *Deinococcus radiodurans,* a bacterium that can live through radiation so intense the glass of a Pyrex beaker holding them is cooked to a discolored and fragile state. A human being exposed to 1,000 rads of radiation energy, a dose delivered in the atomic explosions at Hiroshima and Nagasaki, dies within one or two weeks. At 1,000 times this amount, 1 million rads, the growth of the *Deinococcus* is slowed, but all the bacteria still survive. At 1.75 million rads, 37 percent make it through, and even at 3 million rads a very small number still endure. The secret of this superbug is its extraordinary ability to repair broken DNA. All organisms have an enzyme that can replace chromosome parts that have been shorn off, whether by radiation, chemical insult, or accident. The more conventional bacterium *Escherichia coli,* a dominant inhabitant of the human gut, can repair two or three breaks at one time. The superbug can manage five hundred breaks. The special molecular techniques it uses remain unknown.

Deinococcus radiodurans and its close relatives are not just extremophiles but ultimate generalists and world travelers, having been found, for example, in llama feces, Antarctic rocks, the tissue of Atlantic haddock, and a can of ground pork and beef irradiated

by scientists in Oregon. They join a select group, also including cyanobacteria of the genus *Chroococcidiopsis,* that thrive where very few other organisms venture. They are Earth's outcast nomads, looking for life in all the worst places.

By virtue of their marginality, the superbugs are also candidates for space travel. Microbiologists have begun to ask whether the hardiest among them might drift away from Earth, propelled by stratospheric winds into the void, eventually to settle alive on Mars. Conversely, indigenous microbes from Mars (or beyond) might have colonized Earth. Such is the theory of the origin of life called panspermia, once ridiculed but now an undeniable possibility.

The superbugs have also given a new shot of hope to exobiologists, scientists who look for evidences of life on other worlds. Another stimulus is the newly revealed existence of SLIMEs (subsurface lithoautotrophic microbial ecosystems), unique assemblages of bacteria and fungi that occupy pores in the interlocking mineral grains of igneous rock beneath Earth's surface. Thriving to a depth of up to two miles or more, they obtain their energy from inorganic chemicals. Because they do not require organic particles that filter down from conventional plants and animals whose ultimate energy is from sunlight, the SLIMEs are wholly independent of life on the surface. Consequently, even if all of life as we know it were somehow extinguished, these microscopic troglodytes would carry on. Given enough time, a billion years perhaps, they would likely evolve new forms able to colonize the surface and resynthesize the precatastrophe world run by photosynthesis.

The major significance of the SLIMEs for exobiology is the heightened possibility they suggest of life on other planets and Mars in particular. SLIMEs, or their extraterrestrial equivalent, might live deep within the red planet. During its early, aqueous period Mars had rivers, lakes, and perhaps time to evolve its own surface organisms. According to one recent estimate, there was enough water to cover the entire Martian surface to a depth of five hundred meters. Some, perhaps most, of the water may still exist in permafrost, surface ice covered by the dust we now see from our landers—or, far below the surface, in liquid form. How far below? Physicists believe there is enough heat inside Mars to liquefy water. It comes from a combination of decaying radioactive minerals, some gravitational heat remaining from the original assembly of the planet out of smaller cosmic fragments, and gravitational energy from the sinking of heavier elements and rise of lighter ones. A recent model of the combined effects suggests that the temperature of Mars increases with depth in the upper crustal layers at a rate of 6°F per mile. As a consequence, water could be liquid at eighteen miles beneath the surface. But some water may well up occasionally from the aquifers. In 2000, high-resolution scans by an orbiting satellite revealed the presence of gullies that may have been cut by running streams in the last few centuries or even decades. If Martian life did arise on the planet, or arrived in space particles from Earth, it must include extremophiles, some of which are (or were) ecologically independent single-celled organisms able to persist in or beneath the permafrost.

An equal contender for extraterrestrial life in the solar system is Europa, the second moon out (after Io) of Jupiter. Europa is ice-covered, and long cracks and filled-in meteorite craters on its surface suggest there is an ocean of brine or slurried ice beneath the surface. The evidence is consistent with the likelihood of persistent interior heat in Europa caused by its gravitational tug of war with nearby Jupiter, Io, and Callisto. The main ice crust may be six miles thick, but crisscrossed with far thinner regions on top of upwelling liquid water, thin enough in fact to create slabs that move like icebergs. Do SLIME-like autotrophs float and swim in the Europan Ocean beneath? To planetary scientists and biologists the odds appear good enough to have a look, and practical enough to test—if we can soft-land probes on the upwelling surface cracks and drill through the ice skims that cover them. A second, although less promising, candidate is Callisto, the most distant of

Jupiter's larger moons, which may have an ice crust about sixty miles thick and an underlying salt ocean up to twelve miles deep.

On Earth, the closest approach to the putative oceans of Europa and Callisto is Antarctica's Lake Vostok. About the size of Lake Ontario, with depths exceeding 1,500 feet, Vostok is located under two miles of the East Antarctic Ice Sheet in the remotest part of the continent. It is at least one million years old, wholly dark, under immense pressure, and fully isolated from other ecosystems. If any environment on Earth is sterile, it should be Lake Vostok. Yet this hidden world contains organisms. Scientists have recently drilled through the glacial ice to the six-hundred-foot bottom layer adjacent to the lake. The lowest core samples contained a sparse diversity of bacteria and fungi almost certainly derived from the underlying water. The drill will not be pushed on down into the liquid water. To do so would contaminate one of the last remaining pristine habitats on Earth. The Vostok operation, while telling us very little as yet about the possibility of extraterrestrial life, is a precursor of similar probes likely to be conducted during this century on Mars and the Jovian moons Europa and Callisto.

Suppose that autotrophs parallel to those on Earth originated without benefit of sunlight. Could they have also given rise in the stygian darkness to animals of some kind? The image leaps to mind of crustaceanlike species filtering the microbes and larger, fishlike animals hunting the crustaceoids. A recent discovery on planet Earth suggests that such independent evolution of complex life forms can occur. Romania's Movile Cave was sealed off from the outside more than 5.5 million years ago. During that time it evidently received oxygen through minute cracks in the overlying rocks, but no organic material from the sunlight-driven flora and fauna in the world above. Although the peculiar life forms of most caves around the world draw at least part of their energy from the outside, this is evidently not the case for the Movile Cave and may never have been. The energy base is the autotrophic bacteria, which metabolize hydrogen sulfide from the rocks. Feeding on them and each other are no fewer than forty-eight species of animals, of which thirty-three proved new to science when the cave was explored. The microbe grazers, equivalent to plant eaters on the outside, include pill bugs, springtails, millipedes, and bristletails. Among the carnivores that hunt the microbe grazers are pseudoscorpions, centipedes, and spiders. These more complex organisms are descended from ancestors that entered before the cave was sealed. A second example of an independent stygian system, although not entirely closed to the outside, is Cueva de Villa Luz (Cave of the Lighted House), on the edge of the Chiapas highlands in Tabasco, southern Mexico. Here too the energy base is metabolism by the autotrophic bacteria. Forming layers over the inner cave walls, they subsist on hydrogen sulfide and support a multifarious swarm of small animals.

Studies of the distribution of life have revealed several fundamental patterns in the way species proliferate and are fitted together in Earth's far-flung ecosystems. The first, the most elementary, is that bacteria and archaeans occur everywhere there is life of any kind, whether on the surface or deep beneath it. The second is that, if there is even the smallest space through which to wriggle or swim, tiny protists and invertebrates invade and proceed to prey on the microbes and one another. The third principle is that the more space available, up to and including the largest ecosystems such as grasslands and oceans, the larger are the largest animals living in them. And finally, the greatest diversity of life, as measured by the number of species, occurs in habitats with the most year-round solar energy, the widest exposure of ice-free terrain, the most varied terrain, and the greatest climatic stability across long stretches of time. Thus the equatorial rainforests of the Asian, African, and South American continents possess by far the largest number of plant and animal species.

Regardless of its magnitude, biodiversity (short for biological diversity) is everywhere organized into three levels. At the top are the ecosystems, such as rainforests, coral reefs, and lakes. Next are

the species, composed of the organisms in the ecosystems, from algae and swallowtail butterflies to moray eels and people. At the bottom are the variety of genes making up the heredity of individuals that compose each of the species.

Every species is bound to its community in the unique manner by which it variously consumes, is consumed, competes, and cooperates with other species. It also indirectly affects the community in the way it alters the soil, water, and air. The ecologist sees the whole as a network of energy and material continuously flowing into the community from the surrounding physical environment, and back out, and then on round to create the perpetual ecosystem cycles on which our own existence depends.

It is easy to visualize an ecosystem, especially if it is as physically discrete as, say, a marsh or an alpine meadow. But does its dynamical network of organisms, materials, and energy link it to other ecosystems? In 1972 the British inventor and scientist James E. Lovelock said that, in fact, it is tied to the entire biosphere, which can be thought of as a kind of superorganism that surrounds the planet. This singular entity he called Gaia, after Gaea, or Ge, a vaguely personal goddess of early Greece, giver of dreams, divine personification of Earth, and object of the cult of Earth, as well as mother of the seas, the mountains, and the twelve Titans—in other words, *big*. There is considerable merit in looking at life in this grand holistic manner. Alone among the solar planets, Earth's physical environment is held by its organisms in a delicate equilibrium utterly different from what would be the case in their absence. There is plenty of evidence that even some individual species have a measurable global impact. In the most notable example, the oceanic phytoplankton, composed of microscopic, photosynthesizing bacteria, archaeans, and algae, is a major player in the control of the world climate. Dimethylsulfide generated by the algae alone is believed to be an important factor in the regulation of cloud formation.

The concept of the biosphere as Gaia has two versions: strong and weak. The strong version holds that the biosphere is a true superorganism, with each of the species in it optimized to stabilize the environment and benefit from balance in the entire system, like cells of the body or workers of an ant colony. This is a lovely metaphor, with a kernel of truth, providing the idea of superorganism is broadened enough. The strong version, however, is generally rejected by biologists, including Lovelock himself, as a working principle. The weak version, on the other hand, which holds that some species exercise widespread and even global influence, is well substantiated. Its acceptance has stimulated important new programs of research.

Looking at the totality of life, the POET asks, Who are Gaia's children?

The ECOLOGIST responds, They are the species. We must know the role each one plays in the whole in order to manage Earth wisely.

The SYSTEMATIST adds, Then let's get started. How many species exist? Where are they in the world? Who are their genetic kin?

Systematists, the biologists who specialize in classification, favor the species as the unit by which to measure biodiversity. They build on the system of classification invented in the mid-1700s by the Swedish naturalist Carolus Linnaeus. In the Linnaean system each species is given a two-part Latinized name such as *Canis lupus,* for the gray wolf, with *lupus* being the species and *Canis* the genus of wolves and dogs. Similarly, all of humanity composes the species *Homo sapiens.* Today there is only one member of our very distinctive genus, but as recently as 27,000 years ago there was also *Homo neanderthalensis,* the Neanderthal people who preceded *Homo sapiens* in glacier-bound Europe.

The species is the base of the entire Linnaean system and the unit by which biologists traditionally visualize the span of life. The higher categories from genus to domain are simply the means by which the degrees of similarity are subjectively assayed and roughly described. When we say *Homo neanderthalensis,* we mean a species close to *Homo sapiens;* when we say *Australopithecus africanus,* to designate one of the ancestral man-apes, we mean a creature different enough from the species of *Homo* to be placed in

another genus, *Australopithecus.* And when we assert that all three of the species composing two genera are hominids, we mean they are close enough to one another to be classified as members of the same family, the Hominidae. The closest living relations of the Hominidae are the common chimpanzee, *Pan troglodytes,* and the pygmy chimpanzee, or bonobo, *Pan paniscus.* They are similar enough to each other, and share sufficiently close common ancestry, to be put in the same genus, *Pan.* And both are different enough from the hominids, with distant enough common ancestry, to constitute not only a distinct genus but a separate family, the Pongidae. The Pongidae also includes a second genus for the orangutan and a third for the two species of gorillas.

And thus in visualizing life we travel nomenclaturally outward through the gossamer pavilions of Earth's biodiversity. The principles of higher classification are very easy to grasp, once you get used to the Latinized names. The Linnaean system builds up hierarchically to the higher categories of biodiversity by the same basic principles used to organize ground combat troops, proceeding from squads to platoons to companies to divisions to corps to armies. Returning to the gray wolf, its genus *Canis,* the common dogs and wolves, are placed into the family Canidae with other genera that hold the species of coyotes and foxes. Families are grouped into orders; the order Carnivora are all the canids plus the families respectively of bears, cats, weasels, raccoons, and hyenas. Orders are clustered into classes, with the class Mammalia composed of the carnivores and all other mammals, and classes are clustered into phyla, in this particular progression the phylum Chordata, which includes mammals and all other vertebrates as well as the vertebra-less lancelets and sea squirts. Thence phyla into kingdoms (Bacteria, Archaea, Protista, Fungi, Animalia, Plantae); and finally, at the summit, encompassing everything, there are the three great domains of life on Earth, the Bacteria, the Archaea, and the Eukarya, the last comprising the protistans (also called protozoans), fungi, animals, and plants.

But always, the real units that can be seen and counted as corporeal objects are the species. Like troops in the field, they are present and waiting to be counted, regardless of how we arbitrarily group and name them. How many species are there in the world? Somewhere between 1.5 and 1.8 million have been discovered and given a formal scientific name. No one has yet made an exact count from the taxonomic literature published over the past 250 years. We know this much, however: the roster, whatever its length, is but a mere beginning. Estimates of the true number of living species range, according to the method used, from 3.6 million to 100 million or more. The median of the estimates is a little over 10 million, but few experts would risk their reputations by insisting on this figure or any other, even to the nearest million.

The truth is that we have only begun to explore life on Earth. How little we know is epitomized by bacteria of the genus *Prochlorococcus,* arguably the most abundant organisms on the planet and responsible for a large part of the organic production of the ocean—yet unknown to science until 1988. *Prochlorococcus* cells float passively in open water at 70,000 to 200,000 per milliliter, multiplying with energy captured from sunlight. Their extremely small size is what makes them so elusive. They belong to a special group called picoplankton, forms even smaller than conventional bacteria and barely visible even at the highest optical magnification.

The blue ocean teems with other novel and little-known bacteria, archaeans, and protozoans. When researchers began to focus on them in the 1990s, they discovered that these organisms are vastly more abundant and diverse than anyone had previously imagined. Much of this miniature world exists in and around previously unseen dark matter, composed of wispy aggregates of colloids, cell fragments, and polymers that range in diameter from billionths to hundredths of a meter. Some of the material contains "hot spots" of nutrients that attract scavenger bacteria and their tiny bacterial and protozoan predators. The ocean we peer into, seemingly clear with only an occasional fish and invertebrate passing beneath, is not the ocean we thought. The visible organisms are just the tip of a vast biomass pyramid.

Among the multicellular organisms of Earth in all environments, the smallest species are also the least known. Of the fungi, which are nearly as ubiquitous as the microbes, 69,000 species have been identified and named, but as many as 1.6 million are thought to exist. Of the nematode worms, making up four of every five animals on Earth and the most widely distributed, 15,000 species are known, but millions more may await discovery.

During the molecular revolution in biology, which spanned the second half of the twentieth century, systematics was judged to be a largely outdated discipline. It was pushed aside and kept on minimal rations. Now the renewal of the Linnaean enterprise is seen as high adventure; systematics has returned to the center of the action in biology. The reasons for the renaissance are multiple. Molecular biology has provided systematics the tools to speed the discovery of microscopic organisms. New techniques are now available in genetics and mathematical tree theory to trace the evolution of life in a swift and convincing manner. All this has happened just in time. The global environmental crisis gives urgency to the full and exact mapping of all biological diversity.

One of the open frontiers in biodiversity exploration is the floor of the ocean, which from surf to abyss covers 70 percent of Earth's surface. All of the thirty-six known animal phyla, the highest-ranking and most inclusive groups in the taxonomic hierarchy, occur there, as opposed to only ten on the land. Among the most familiar are the Arthropoda, or the insects, crustaceans, spiders, and their sundry relations; and the Mollusca, comprising the snails, mussels, and octopuses. Amazingly, two marine phyla have been discovered during the past thirty years: the Loricifera, miniature bullet-shaped organisms with a girdlelike band around their middle, described for the first time in 1983; and the Cycliophora, plump symbiotic forms that attach themselves to the mouths of lobsters and filter out food particles left over from their hosts' meals, described in 1996. Swarming around the loriciferans and cycliophorans, and deep into the soil of shallow marine waters, are other Alice-in-Wonderland creatures, the meiofauna, most of them barely visible to the naked eye. The strange creatures include gastrotrichs, gnathostomulids, kinorhynchs, tardigrades, chaetognaths, placozoans, and orthonectids, along with nematodes and worm-shaped ciliate protozoans. They can be found in buckets of sand drawn from the intertidal surf and offshore shallow water around the world. So, for those seeking a new form of recreation, plan a day at the nearest beach. Take an umbrella, bucket, trowel, microscope, and illustrated textbook on invertebrate zoology. Don't build sand castles but explore, and as you enjoy this watery microcosm keep in mind what the great nineteenth-century physicist Michael Faraday correctly said, that nothing in this world is too wonderful to be true.

Even the most familiar small organisms are less studied than might be guessed. About ten thousand species of ants are known and named, but that number may double when tropical regions are more fully explored. While recently conducting a study of *Pheidole*, one of the world's two largest ant genera, I uncovered 341 new species, more than doubling the number in the genus and increasing the entire known fauna of ants in the Western Hemisphere by 10 percent. As my monograph went to press in 2001, additional new species were still pouring in, mostly from fellow entomologists collecting in the tropics.

You will recognize this frequent image in popular entertainment: a scientist discovers a new species of animal or plant (perhaps after an arduous journey up a tributary of the Orinoco). His team at base camp celebrates, opening a bottle of champagne, and radios the news to the home institution. The truth, I assure you, is almost always different. The small number of scientists expert in the classification of each of the most diverse groups, from bacteria to fungi and insects, are inundated with new species almost to the breaking point. Working mostly alone, they try desperately to

keep their collections in order while eking out enough time to publish accounts of a small fraction of the novelties sent to them for identification.

Even the flowering plants, traditionally a favorite of field biologists, retain large pockets of unexamined diversity. About 272,000 species have been described worldwide, but the true number is likely to be 300,000 or more. Each year about 2,000 new species are added to the world list published in botany's standard reference work, the *Index Kewensis.* Even the relatively well-curried United States and Canada continue to yield about 60 new species annually. Some experts believe that as much as 5 percent of the North American flora await discovery, including 300 or more species and races in the biologically rich state of California alone. The novelties are usually rare but not necessarily shy and inconspicuous. Some, like the recently described Shasta snow-wreath *(Neviusia cliftonii),* are flamboyant enough to serve as ornamentals. Many grow in plain sight. A member of the lily family, *Calochortus tiburonensis,* first described in 1972, grows just ten miles from downtown San Francisco. In 1982, a twenty-one-year-old amateur collector, James Morefield, discovered the brand-new leather flower, *Clematis morefieldii,* on the outskirts of Huntsville, Alabama.

Ever deeper rounds of zoological exploration, driven by a sense of urgency over vanishing environments, have revealed surprising numbers of new vertebrates, many of which are placed on the endangered list as soon as they are discovered. The global number of amphibian species, including frogs, toads, salamanders, and the less familiar tropical caecilians, grew between 1985 and 2001 by one third, from 4,003 to 5,282. There can be little doubt that in time it will pass 6,000.

The discovery of new mammals has also continued at a rapid pace. Collectors, by journeying to remote tropical regions and concentrating on small elusive forms such as tenrecs and shrews, have increased the global number in the last two decades from about 4,000 to 5,000. The record for rapid discovery during the past half-century was set by James L. Patton in July 1996. With just three weeks' effort in the central Andes of Colombia, he discovered 6 new species—four mice, a shrew, and a marsupial. Even primates, including apes, monkeys, and lemurs, the most sought of all mammals in the field, are yielding novelties. In the 1990s alone Russell Mittermeier and his colleagues managed to add 9 new species to the 275 previously known. Mittermeier, whose searches take him to tropical forests around the world, estimates that at least another hundred species of primates await discovery.

New land mammals of large size are a rarity, but even a few of them continue to turn up. Perhaps the most surprising find in recent memory was the discovery during the mid-1990s of not one but four big animals in the Annamite Mountains between Vietnam and Laos. Included are a striped hare; a seventy-five-pound barking deer, or giant muntjac; and a smaller, thirty-five-pound barking deer. But most astonishing is the two-hundred-pound cowlike animal called saola, or "spindlehorn," by the local people and Vu Quang bovid by zoologists. It was the first land vertebrate of this size to be discovered for more than fifty years. The saola is not closely related to any other known ungulate mammal. It has been placed in a genus of its own, *Pseudoryx*, meaning false oryx, in reference to its superficial resemblance to the true oryx, a large African antelope. Only a few hundred saola are thought to exist. Their numbers are probably dwindling fast from native hunting and the clearing of the forests in which they live. No scientist has yet seen one in the wild, but in 1998 a photograph was captured by a pressure-released trap camera. And for a short time, before she died, a female brought in by Hmong hunters was kept in the zoo at Lak Xao, Laos.

For centuries, birds have been the most pursued and best known of all animals, but here again new species are still coming to light at a steady pace. From 1920 to 1934, the golden age of ornithological field research, an average of about ten subsequently authenticated species were described each year. The number dropped to between two and three and remained steady thereafter into the 1990s. By the end of the century, approximately ten thousand valid species were securely established in the world register. Then, an unexpected revolution in field studies opened the census to a flood of new candidate species. Experts had come to recognize the possible existence of large numbers of sibling species—populations closely resembling one another in anatomical traits traditionally used in taxonomy, such as size, plumage, and bill shape, yet differing strongly in other, equally important traits discoverable only in the field, such as habitat preference and mating call. The fundamental criterion used to separate species of birds, as well as most other kinds of animals, is that provided by the biological species concept: populations belong to different species if they are incapable of interbreeding freely under natural conditions. As field studies have increased in sophistication, more such genetically isolated populations have come to light. Old species recently subdivided into multiple species include the familiar *Phylloscopus*, leaf warblers, of Europe and Asia and, more controversially, the crossbills of North America. An important new analytic method is song playback, in which ornithologists record the songs of one population and play them in the presence of another population. If the birds show little interest in each other's songs, they can be reasonably assumed to represent different species, because they would presumably not interbreed if they met in nature. The playback method makes possible for the first time the evaluation not only of populations occupying the same range but also those living apart and classified as geographic races, or subspecies. It is not out of the question that the number of validated living bird species will eventually double, to twenty thousand.

More than half the plant and animal species of the world are believed to occur in the tropical rainforests. From these natural greenhouses, which occupy the opposite end of the biodiversity scale from the McMurdo Dry Valleys, many world records of biodiversity have been reported: 425 kinds of trees in a single hectare (2.5 acres) of Brazil's Atlantic Forest, for example, and 1,300 butterfly species from a corner of Peru's Manu National Park. Both numbers are ten times greater than those from comparable sites in Europe and North America. The record for ants is 365 species from 10 hectares (25 acres) in a forest tract of the upper Peruvian Amazon. I have identified 43 species from the canopy of a single *tree* in the same region, approximately equal to the ant fauna of all the British Isles.

These impressive censuses do not exclude a comparable richness of some groups of organisms in other major environments of the world. A single coral head in Indonesia can harbor hundreds of species of crustaceans, polychaete worms, and other invertebrates, plus a fish or two. Twenty-eight kinds of vines and herbaceous plants have been found growing on a giant *Podocarpus* yellowwood conifer in the temperate rainforest of New Zealand, setting the world record for vascular epiphytes on a single tree. As many as two hundred species of mites, diminutive spiderlike creatures, teem in a single square meter of some hardwood forests of North America. In the same spot a gram of soil—a pinch held between thumb and forefinger—contains thousands of species of bacteria. A few are actively multiplying, but most are dormant, each awaiting the special combination of nutrients, moisture, aridity, and temperature to which its particular strain is adapted.

You do not have to visit distant places, or even rise from your seat, to experience the luxuriance of biodiversity. You yourself are a rainforest of a kind. There is a good chance that tiny spiderlike mites build nests at the base of your eyelashes. Fungal spores and hyphae on your toenails await the right conditions to sprout a Lilliputian forest. The vast majority of the cells in your body are not your own; they belong to bacterial and other microorganismic species. More than four hundred such microbial species make their home in your mouth. But rest easy: the bulk of protoplasm you carry around is still human, because microbial cells are so small. Every time you scuff earth or splash mud puddles with your

shoes, bacteria, and who knows what else, that are still unknown to science settle on them.

Such is the biospheric membrane that covers Earth, and you and me. It is the miracle we have been given. And our tragedy, because a large part of it is being lost forever before we learn what it is and the best means by which it can be savored and used.