

WEIRD LIFE



The Search
for Life That Is
Very, Very Different
from Our Own

DAVID TOOMEY

“Weird indeed, and not a little wonderful.”

—*Nature*

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Prologue

One of my favorite books as a child (and, truth be told, one of my favorites today) is Dr. Seuss's *I Ran the Zoo*. The "I" of the title is Gerald McGrew, a boy of perhaps age ten or twelve. The book opens as young McGrew visits his local zoo and finds its animals—a few sleepy-eyed bears and lions—uninspiring. He wishes for more exotic creatures, and so begins an extended daydream. Our youthful protagonist imagines himself as the zoo's manager, releasing the bears and lions, which shamle off, one presumes, to find more stimulating environs. Then he fantasizes himself the zoo's procurer, outfitted with pith helmet and butterfly net, in the heroic mold of Mallory and Burto scaling mountains and crossing oceans in search of ever more exotic animals. And he finds them. In the "Desert of Zind" he captures a ferocious sort of camel called a "Mulligatawny," and on the "Island of Gwark" he catches a gigantic bird called a "Fizza-ma-Wizza-ma-Dill." And then he assures us that he's just warming up.

Young Gerald McGrew may be a fictional character in a children's book, but his urges resonate. Humans, it seems, have always been less than satisfied with actual fauna, and so moved to invent alternatives. We all remember a few: the sphinx, the griffin, the basilisk, the phoenix. But ancient cultures created many more. Margaret Robinson's *Fictitious Beasts* (one of the most thorough and authoritative catalogues) lists several hundred, each description replete with details of behavior and in many cases an instructive encounter with a god or heroic mortal.¹ To a biologist, what is striking about this imaginary bestiary, especially in comparison with the bestiary that nature actually has produced, is its paucity. The fact is that no one knows exactly how many species reside on our planet at present, but a conservative guess is 3.6 million, and some estimates are as high as 100 million.² To those who prefer the real to the imaginary, it should come as good news that Robinson's work has a real-world cognate. The *Encyclopedia of Life*, an effort to build an online compendium of every extant species, is now at 500,000 web pages and growing.

Peruse Robinson's work at a rate of a second per page, and you'll close the back cover after about four minutes. To get through the *Encyclopedia of Life* at the same rate you'll need six weeks. Even then, you'll have only a hint of the astonishing diversity of life over time. There have been at least 3 billion distinct species in the history of Earth.³ Suppose there were a book devoting a page to each species. To read it at a rate of a second per page, you'd need nearly ten centuries.

It's not just the numbers. By comparison with reality, the creatures of myth suffer in another way. Most are little more than portmanteaus—with, for instance, the head of one animal sewn onto the body of another. Any imaginatively sadistic schoolchild equipped with scissors and glue, you might think, could do as well. Even the parts list is severely scaled back, derived, as it is, almost entirely from the single branch of the tree of life that bears mammals, lizards, and birds. There are exceptions, like "Grandmother Spider," who figures in many Native American creation myths; and the kraken, the giant squid that inhabits the imaginations of coastal dwellers on several continents. And there are some rather wondrous hybrids. The "vegetable lamb of Tartary" (*Agnus scythicus* or *Planta Tartarica*)

Barometz), for instance, was a legendary plant of central Asia believed to grow sheep as its fruit. The sheep were connected to the plant by an umbilical cord, and when they had eaten all they could reach the whole plant withered and died.⁴ But that is about as bizarre as the mythical beasts get. The overwhelming majority, if we were to classify them within standard *taxonomies*, would be *vertebrates* in the phylum Chordata—essentially, animals with backbones.

For most of human history, anyone seeking a little strangeness in the proportion had to be satisfied with these. Then, in the mid-seventeenth century, natural philosophers discovered another bestiary, one that had two advantages over the imagined one. First, its animals were real. Second, they did not inhabit an exotic and distant country. In fact, they lived among us. And on us. A great many of them lived *inside* us.

By the late 1620s, the first of the type of instrument we call the microscope had been crafted and named. Half a century later, a twenty-eight-year-old British naturalist named Robert Hooke began to make his own, to use them to examine a great many things, and to sketch what he saw. Hooke's work was not always easy. He had two sorts of microscopes. One, rather like the instrument we know, was a set of lenses fixed and aligned inside a small tube; the other, far more difficult to use, was a glass bead the size of a pinhead, held in a brass mounting. Of course, the subjects themselves could be uncooperative. The only way Hooke could immobilize ants without half crushing them was to get them drunk on brandy.

Despite such challenges, by 1664 Hooke had produced a work called *Micrographia*. Even now, in an age of high-definition television and IMAX 3D, it can be a startling experience to open the book to a folded page and gently pull its leaves apart to reveal, for instance, a copperplate engraving of a flea measuring a monstrous half meter across. One of Hooke's contemporaries, Samuel Pepys, called the book the "most ingenious" he had ever read. *Micrographia* became a best seller, and many of its readers would have agreed with Hooke's observation of the flea: "the strength and beauty of this small creature, had it no other relation at all to man, would deserve a description."⁵ Still, a few criticized Hooke's pursuit of knowledge with no obvious practical application, and many more were simply uninterested. The reason may have been that the animals discovered by Hooke and his successors were utterly unlike anything known at the time; they were perhaps *too* strange. Of course, there was another reason for the dis-interest: Hooke's creatures were very, very small. Then, as now, humans equate small with unimportant—a prejudice that, as we shall see, is as misguided as it is dangerous.

Some two centuries after *Micrographia*, natural philosophers discovered another bestiary—this one populated by animals that were as large by comparison with us as we are compared to house cats. They are long vanished from the Earth, but their appeal, perhaps especially to a certain demographic of seven-year-olds, has proved enduring. Some of the reasons are obvious. Dinosaurs are strange enough to inspire wonder, but not so strange as to be wholly unfamiliar. *Tyrannosaurus rex* (a favorite of the aforementioned demographic) saw through eyes not unlike our own, breathed through nostrils, and walked over ground.*

As the flea and *Tyrannosaurus rex* demonstrate, nature itself will outperform the uninformed imagination every time. If these creatures showed the limits of human imagination, they also enlarged it. With the discovery of microscopic and sub-microscopic life came questions about nourishment, reproduction, and mobility. Was there cooperation? How small was it possible for a living thing to be? The dinosaurs, likewise, produced new questions. How could such enormous masses be supported? How large was it possible for a living thing to be? And of course, why did they vanish?

Even as naturalists pondered these questions, there came a new understanding of life at fundament

levels. In 1859, Charles Darwin, prodded by the independent discoveries of British naturalist Alfred Russel Wallace, published *On the Origin of Species by Means of Natural Selection*. Despite attacks by religious conservatives, the book was widely read (it would see six editions in Darwin's lifetime), and within a decade several works were published in its support. In the early years of the twentieth century, biologists rediscovered Gregor Mendel's laws of heredity, and American geneticist Walter Sutton found evidence that *chromosomes* carry units of inheritance. In the 1940s, Julian Huxley and George Gaylord Simpson consolidated natural selection and genetics, and *DNA* was found responsible for hereditary changes in bacteria. In 1953, James Watson and Francis Crick published the structure of DNA in the journal *Nature*.

Meanwhile, as to the variety of forms that might be made with that DNA, there were—to the delight of most and the consternation of some—more surprises. Again and again, scientists discovered animals and plants that broke all the rules, surpassing what many had assumed to be limits in size, shape, and behavior. Nonetheless, by the mid-twentieth century most biologists had reason to believe that life would survive within only a narrow range of pressures and temperatures. There seemed to be some limits that could not be surpassed.

By this time there were at least nine specialties in *biology*, the study of living organisms and life processes. Probably it shouldn't be surprising that practitioners in each specialty tended to define life in the terms of that specialty, and that they had no shared definition of the core subject at all. But what is surprising is that no one thought this lack of consensus much of a problem. Taxonomists, molecular biologists, and embryologists went about their business identifying species, studying chemical reactions that maintained a *metabolism*, and culturing *microbes*. If asked to define life by, say, a upstart philosophy major at an interdepartmental faculty reception, they would say they knew it when they saw it and that, thank you, was quite enough.

In the early 1970s, however, it became obvious that the biologists' confidence in their powers of recognition, whether justified or unjustified, was not quite enough. It was about that time that NASA asked scientists to submit designs for life-detecting experiments to be carried to the planet Mars aboard the two unmanned *Viking* spacecraft. These would be the first *in situ* attempts to discover life on another world. To detect something with a miniature laboratory that would be operated remotely by a radio signal sent from a transmitter more than a million miles away was no small challenge. It seemed reasonable that the task would be made easier if the "something" to be detected was properly defined first.

The three experiments chosen by NASA were ingenious but, at least in the view of some, lacking imagination. Two were designed with the assumption that Martian life would need water, and all three were designed under the assumption that life would survive in only a narrow (in fact, a rather Earthlike) range of temperatures. Depending on whom you ask, the results of that reconnaissance meant that either there was no life in the spacecrafts' vicinity or (this from one experiment) there might be some very unusual life indeed. In any case, the results did little to change larger ideas about life's boundaries.

Then, in a series of discoveries in the 1980s and 1990s back on Earth, scientists found that they had underestimated nature's ingenuity; the realm of life was (again) greater than they had dared imagine. In places where no one thought life possible, organisms were not merely surviving; they were thriving. Once biologists began to look, they found them everywhere. And there were enough to satisfy an arm of Gerald McGrews.

No one expected life in water much above its boiling point. But scientists found bacteria living at volcanic hydrothermal vents on the ocean floor, one species merrily reproducing at a scalding 235°

No one thought life could survive in water at temperatures much below its freezing point. But Antarctic ice floes, scientists found channels of slushy brine in which single-celled algae were harvesting energy from the sunlight filtered through ice and assimilating nutrients from the water below.

Biologists had assumed other limits as well. They had thought that organisms would tolerate only a narrow range of pH levels. Then they discovered life flourishing in hot sulfur springs and growing vigorously in soda lakes. They had assumed that aquatic life would tolerate only so much salt. But they found bacteria that had adapted perfectly to saturated salt lakes. They had believed that high levels of radiation would kill any organism. But they discovered a bacterium that, by efficiently repairing broken DNA strands, could withstand radiation energies at a thousand times the level that would kill a human. They had assumed that life required a “substrate”—a surface on which molecules could interact easily and often. But they found microbes that may be living through their entire life cycles—growing, metabolizing, reproducing—in clouds.⁶

Biologists knew that many creatures living in the dark on the seafloor ate organic material that fell slowly from the surface, and that some survived by drawing energy from chemical reactions. Still, they assumed that all life depended—perhaps indirectly but nonetheless ultimately—on the Sun. But in 1996, a group of scientists reported the discovery, more than a mile beneath Earth’s surface, of assemblages of bacteria and fungi that gained all their energy from inorganic chemicals in the rocks around them.

All these organisms—the bacteria in the hydrothermal vent, the algae in the Antarctic brine, the rock-eating fungi, and the rest—came to be known collectively as *extremophiles*—lovers of extremes.

The physical boundaries within which life is possible are unknown and undefined, but most biologists believe that they must exist, for the simple reason that there are temperatures and pressures under which the structures of organisms—cells, DNA, and proteins—will break down, no matter how well protected. In short, life must have *ultimate* limits. If life exists outside them, it must be something other than what has been called, in that venerable phrase that can hardly be improved upon, “life as we know it.” It must be fundamentally different. It must be, in a word, *weird*.

Exactly what can we say about such life? At the very least, we can say what it is not. All life we know has DNA, the same twenty or so amino acids and proteins, and a biochemistry that employs the same thousands of chemical pathways (the complex chemical reactions by which a metabolism is maintained) and that uses liquid water as a solvent. It is for these reasons that biologists believe that all life we know—you, me, the flea, the megalosaurus, Charles Darwin, your neighborhood creationist, and all the extremophiles—is descended from a single common ancestor. Weird life, if it exists, would *not* be descended from that ancestor, and it could be weird in any number of ways. It might have as its basis a molecule other than DNA, it might use other amino acids, or it might use a solvent like ammonia or liquid methane.

Whether such substitutions are possible, or whether the fundamental features of life we know are necessary to all life, is far from clear. But it may be that some, or many, or most of those features are the products of happenstance, and that life on Earth might as easily have taken a different path, the result being organisms whose fundamental features would be utterly different from those we know. What is clear is that the discovery of even one example of such life would profoundly change our understanding of biology. The familiar illustration of all life we know is a great tree, its trunk splitting and splitting again into branches representing phylogenetic categories, each less fundamental and more populous than that from which it sprouted, finally ending in millions of twigs representing individual species. There have been many discoveries of new species, and recently, even a new

phylum.⁷ But an example of another sort of life would mean that the tree *itself* is not unique, and that it may be only one of many, perhaps one in an entire forest. Such a discovery would be cause for humility on our part—another demonstration that we occupy a smaller part of the universe than we now believe. It would also be cause for renewed wonder at a cosmos that is stranger and vastly richer than we now imagine.

Papers on what we now call weird life appeared sixty years ago, but they were few and scattered across disciplines. There was no overview and nothing like an ongoing discussion. The first gesture in those directions came in 2002. NASA and the European Space Agency (ESA) were thinking about (not exactly planning) unmanned missions to the outer Solar System—to Saturn’s moon Titan, Neptune’s moon Triton, to the comets. If life existed in these places, it would be radically different from anything we knew, and radically different from anything that *Viking* looked for on Mars.

The idea is not new, and we’ve seen it again and again in science fiction: An astronaut on a desolate but otherwise unremarkable planet sees what he assumes is an odd rock formation. He looks away, and it moves. He looks back and realizes his mistake, and (as they say) dramatic complications ensue. But this was not science fiction. Now NASA and ESA were taking the possibility of weird life quite seriously, and making it clear that much was at stake. The discovery of extraterrestrial life—whether it developed independently or had migrated from planet to planet via meteor, solar wind, or some other means—would have profound and lasting consequences not merely for the life sciences or even for science in general, but for our understanding of our very place in the universe. But would we recognize life if we saw it? And if we did *not* recognize it, might we, by inattention or carelessness, destroy it?

In 2002 the National Research Council (NRC) assembled a group of twenty-five scientists from research laboratories and institutes across the United States. The group called itself the Committee on the Limits of Organic Life in Planetary Systems, and its task was nothing if not ambitious. Its members were to define life, to identify the traits necessary to life as we know it, and to determine the outer limits of living systems. As if this were not enough, they were handed a second, more provocative challenge: to imagine possibilities for weird life in some detail. For five years they read and discussed papers, collected data, and talked. By summer 2007 they had published a report summarizing their work. It was titled *The Limits of Organic Life in Planetary Systems*.⁸ Publication of the NRC report represented a watershed moment in the history of thinking about the boundaries of life as we know it, and what sort of life might lie beyond those boundaries. It also provides much of the foundation for this book.

A word on nomenclature. New fields of study try on many names, and this one is no exception. The subject of this book might, with varying degrees of justification, be called beta life, hypothetical life, nonstandard life, nonterran life, unfamiliar life, life as we do *not* know it, alternative biology, and (you knew this was coming) Life 2.0. I’ve settled on *weird life* because at the time this book goes to press it seems to enjoy the most widespread usage, and because it conveys with great economy the sense of strangeness the subject deserves.

As we’ll see, in the violent early history of the Solar System, Earth and Mars traded material, some of which may have been biological. A few scientists argue that life we know may have emerged from spores of extraterrestrial origin. For the time being I will sidestep the question of place of origin, and unless otherwise noted, I’ll use the term “familiar life” to mean all life—terrestrial and otherwise—that is descended from the single ancestor of all life we know, allowing for the possibility that that ancestor may have been extraterrestrial. Alternately, I will use “weird life” to mean any organism or organisms—again terrestrial and otherwise—that are *not* descended from that ancestor.

* In the popular imagination, dinosaurs were real enough that Dickens, in *Bleak House*, could use a resident of the Middle Jurassic to add a touch of atmosphere to a rainy day on the outskirts of London. “As much mud in the streets, as if the waters had but newly retired from the face of the earth,” he wrote, “and it would not be wonderful to meet a Megalosaurus, forty feet long or so, waddling like an elephantine lizard up Holborn Hill.” (p. 1)

CHAPTER ONE

Extremophiles

Julie Huber is a marine oceanographer working at the Marine Biological Laboratory in Woods Hole, Massachusetts. She is thirty-four but has an easy laugh that makes her seem even younger, and if you saw her jogging on a beach you might take her for a professional volleyball player. Her accomplishments in the field of oceanography and marine biology are many; she has logged nearly a year on oceangoing research vessels, and made several descents in the most famous of all research submarines, *Alvin*. Her main research focuses on the microbes that live in and beneath the crust of the seafloor. They are organisms that sequester carbon, cycle chemicals, and affect the circulation of ocean water—all of which are activities crucial to the oceans' overall health. Yet these same organisms happen to be, in the language favored by field biologists, “vastly under-sampled.” Consequently, they have been little studied and so are little understood. They are also in places so difficult to reach that if Huber hopes to study them she must use techniques from various disciplines, among them geology, genetics, and molecular chemistry.

Dr. Huber is possessed of a passionate intellect that can catch you by surprise. She will look you straight in the eye and affirm that a certain development in microbiology “really excites the marine sediment community.”¹ While you register the fact that there *is* a marine sediment community and consider that its members could perhaps benefit from some excitement, she is already explaining, in language that is an unself-conscious mash-up of technical and colloquial, the particular challenges of trying to detect organisms by measuring the chemical components of seawater, noting by the way that certain recent work on methanogen diversity is very cool.²

Lately Huber has been, in her words, “chasing seafloor eruptions.” She is particularly interested in organisms that live in the Pacific, near three “seamounts” (oceanographers' term for submarine mountains). All three seamounts are geologically active, and Huber makes periodic visits to each—often more often, to the place on the ocean's surface several kilometers above them. The visits usually hold surprises. In May 2009 she was on a research vessel in the western Pacific, only twelve hours out of port in Samoa, when the remote operating vehicle *Jason*, from 2 kilometers beneath them, began transmitting live, full-color video images of the West Mata volcano erupting. It was 3:00 a.m. on the ship, but everyone—scientists and off-duty crew alike—was crowded into one room watching the televised images of lava flowing, sometimes explosively, from the deepest erupting volcano anyone had ever seen. It was, Huber said, “definitely the coolest thing I've seen on the seafloor,” adding wryly, “and I've seen a lot of seafloor.”³

The water in the samples that *Jason* retrieved from the vicinity of the volcano was as acidic as battery acid, yet it contained living bacteria. There were fewer kinds than at similar sites, and so there was a less diverse *microbial community*—this the phrase used to describe many populations of microbes living together, sharing resources, and in various ways making life better for one another. Whether the relative paucity of kinds means the environment is too harsh for certain organisms,

whether West Mata's young age means that things are just getting started there, is an interesting and open question—one that Huber hopes to answer in the months ahead.

At the moment, Huber is managing several projects simultaneously. Late on a Friday morning in March 2010, she has just received an e-mail from the postdoctoral student studying under her and doing fieldwork on a research vessel near Guam. It seems that they had set markers and moorings on the seafloor and now couldn't find them. Huber gives a "this sort of thing happens all the time" shrug and suspects the culprit is what geologists, rather unromantically, term a "slumping event." In all likelihood a part of the seafloor slid sideways, taking the markers and moorings with it. Just another reminder, not that Huber needed reminding, that the seafloor is not the grave-quiet place that only half a century ago, many scientists believed it to be.

Huber's research may trace its origins, quite directly, to the discovery in 1977 of the so-called hydrothermal vent communities, and less directly to questions that arose in the first decades of the twentieth century—as to why the continents are shaped as they are.

A SCIENTIFIC MYSTERY

Anyone who sees a world map centered on the Atlantic Ocean cannot help but notice that the eastern coast of South America seems made to fit, jigsaw puzzle-like, into the inward-bending coast of Africa. In 1922 a German geologist and meteorologist named Alfred Wegner went several steps further. Assembling the evidence of fossils, mineral deposits, and scars left by glaciers, he proposed that the comparison was apt. The continents *were* pieces of a puzzle, pieces that happened to be slowly drifting apart. In the decades that followed, others developed Wegner's hypothesis into a theory of plate tectonics, which proposed that the Earth's crust is composed of plates—perhaps ten "major" ones and as many as thirty "minor" ones. It was thought that their upper parts were brittle, their lower parts warmer and more malleable, and that some might be as much as 80 kilometers thick. Geologists found evidence that molten rock was pushing into the seams where the plates had pulled apart.

If this were the case, it might help to answer a question that was surprisingly long-standing and surprisingly straightforward: Why is the chemistry of seawater what it is? Lakes like the Dead Sea—lakes with no outlet other than evaporation—are called "closed basins." They are alkaline in the extreme, and they grow more alkaline over time. Logically, since the world's oceans have no outlet like very large closed-basin lakes, they should be very, very alkaline. Yet their pH, the measure of the acidity or alkalinity of a solution, was between 7.5 and 8—very near the middle of the scale—and that was the case for foaming breakers in the Florida Keys; for dark, dense water in the Mariana Trench; and for the frigid water lapping Antarctic icebergs. It seemed clear that some process was at work filtering the water and maintaining the pH, and doing it everywhere. A few scientists began to suspect undersea hot springs, and they had ideas as to their whereabouts. Hot springs on the Earth's surface were heated by the molten rock in nearby volcanoes; it seemed reasonable to expect that hot springs on the seafloor would also be near molten rock. And many thought there was molten rock in the seams between tectonic plates. Find the seams, many suspected, and you'd find the hot springs.

But no one knew for sure. Even by the early 1970s, textbooks in oceanography introduced the subject with the startling fact that we knew less about the ocean floor than we knew about the near side of the Moon. If anything, this appraisal was generous. Sonar for mapping the floor was crude, and equipment used to measure temperatures and pressures was towed on cables behind ships. Sooner or later a cable would snag on an undersea rise, and the ship would idle its engines while a dispirited crew pulled the equipment aboard. It usually came back wrecked—unless the cable just broke, in which case it didn't come back at all.

The United States Navy, however, had developed sophisticated techniques for mapping the ocean and by the mid-1970s the navy had begun to share them with researchers. Using these techniques, scientists at Woods Hole Oceanographic Institution (WHOI) implemented a three-stage method to explore a swath of seafloor. First, the research ship *Knorr* would drop transponders. Because the seafloor is uneven, they would settle at different depths. Then their positions were measured with great precision by sonar, allowing researchers to derive a low-resolution map of the terrain. Finally, a camera vehicle—a 1.5-ton “gorilla cage” mounted with cameras, strobe lights, and power supplies—would be towed over the terrain at a cautious 4 kilometers an hour, 20 meters above the seafloor. Every few hours the crew would haul the vehicle aboard, pull the film, and develop it.

In the spring of 1977, Woods Hole researchers on the *Knorr* were mapping the seafloor in the eastern Pacific about 280 kilometers northeast of the Galápagos Islands. After one run over terrain 2 kilometers deep, the film showed white clams. It was obvious they were alive.

At such moments the research submarine *Alvin* (owned by the United States Navy and operated by WHOI) would be called into play. By the 1970s she was already something of a workhorse. In 1966 she had been lost once and recovered. Two years earlier, when an air force B-52 bomber collided with a tanker over the Mediterranean Sea and (accidentally) dropped an undetonated hydrogen bomb, *Alvin* was given its moment in Cold War history and summoned to search the ocean floor off Spain. On March 17, 1966, *Alvin*'s pilots found the bomb resting on the seafloor nearly 910 meters deep. It was raised intact. By 1977 *Alvin* had had several upgrades, but its fastest speed was a modest 4 kilometers an hour, and its lights penetrated only 15 meters. Not that any of this mattered. What *Alvin* was especially good for, and what she is still good for, is close observation. And so, when the *Knorr* found live clams 2 kilometers beneath the surface, *Alvin* was towed to the site.

Alvin's crew compartment, a hollow titanium sphere 3 meters across, holds three—a pilot and two researchers. The researchers for this particular investigation were geologists—John Corliss of Oregon State University and John Edmond of MIT. They spent most of the 2,000-meter descent peering out of the Plexiglas portholes. There wasn't much to see, and even when they were a few meters above the sloping seafloor, *Alvin*'s lights illuminated nothing but the hardened molten rock that geologists call pillow basalt. It covered the sloping floor in all directions, making for a scene that, even to a geologist, was not particularly remarkable. Then they noticed something about the water itself. It was shimmering like the air over a hot grill. Hurriedly, Corliss and Edmond took measurements and found that the water was warmer than water at this depth should be, by about 4 degrees.

The pilot took *Alvin* up the slope, and when they neared the crest of a ridge they were astonished to see, lit by the searchlight and through the shimmering water, reefs of mussels, giant clams, crab anemones, and fish. It was a fantastic undersea garden, an oasis vibrant with life. Corliss and Edmond did not know how the riotous island *ecosystem* around them was possible. They did know, however, that *Alvin* had only five hours of power remaining, and they spent that time, Edmond would later write, “in something close to a frenzy,” measuring water temperature, conductivity, pH, and oxygen content, and taking samples of everything that *Alvin*'s mechanical arm could grab.⁴ That evening back aboard the *Knorr*, there was a small celebration. Someone had a camera and snapped photos of Corliss and Edmond—young men, bleary-eyed and smiling.

In 1830, British naturalist Edward Forbes claimed that because sunlight could not penetrate deeper than 600 meters, phytoplankton could not survive below that depth. Without phytoplankton, there was no base for a food chain. It followed, reasonably enough, that the deep ocean must be sterile.⁵ By the mid-twentieth century, the processes by which oceanic life sustains itself were well understood. Sunlight supplies the energy. Nutrients in the form of nitrogen and phosphorus are brought in by rivers

and streams and stirred up from the seafloor by upwelling currents. The floating single-celled plants called phytoplankton use the sunlight, nutrients, and carbon dioxide dissolved in the water. They are eaten by the tiny invertebrates called zooplankton that float freely throughout the seas and other bodies of water, and the zooplankton are eaten by shrimp and other crustaceans, all the way up the food chain to the braised tuna with lemon on your dinner plate. Obviously, such processes could operate only near the ocean surface.

In the decades that followed, however, scientists came to realize that there *was* life at great depths. Fish, crabs and other organisms lived in total darkness at enormous pressures, and survived by feeding on dead and decaying matter that sank slowly from the waters above. By the mid-twentieth century, advances in nautical engineering allowed biologists to see this life firsthand. In the mid-1940s the Swiss scientist Auguste Piccard designed a vessel he called a “bathyscaphe.” Unlike its predecessor, the bathysphere, a simple spherical pressure chamber lowered and raised by a cable, Piccard’s new design featured a float chamber for buoyancy and a separate pressure sphere for the crew. The first bathyscaphe Piccard built was called the *Trieste*. It was sold to the United States Navy in 1957, and three years later it took Jacques Piccard (Auguste’s son) and navy Lieutenant Don Walsh to the bottom of an undersea canyon called the Mariana Trench. It was there that they noticed, more than 11 kilometers beneath the surface, the deepest place in any ocean on Earth, a flatfish.⁶

Still, even in 1977, most marine biologists expected such organisms would be few and solitary. And since recycling of decaying matter in the ocean’s upper levels is fairly efficient and allows very little to sink much lower before it is consumed, they expected those organisms to be quite hungry. So in 1977, when the Woods Hole expedition’s chief scientist called a marine biologist named Holger Jannasch to give him the news of a thriving community of life 2 kilometers deep, Jannasch simply didn’t believe him. “He was,” Jannasch explained, “a geologist, after all.”⁷

The expedition would conduct fourteen more descents to the site. It became apparent that Corliss and Edmond had happened upon a hot-spring field. Warm water was flowing up through every crack and fissure in a roughly circular patch of seafloor about 100 meters across. While *Alvin* investigated the newfound life below, scientists aboard the *Knorr* studied the water samples already returned, and found that all had a high concentration of hydrogen sulfide. That turned out to be a thread that would tie together an entire *ecology*.

On land, some bacteria were known to derive energy from hydrogen sulfide through a process called chemosynthesis. They were rare, and most organisms took their energy, directly or indirectly, through photosynthesis. But in the dark 2 kilometers deep, chemosynthesis might be the only synthesis possible. Soon, researchers at Woods Hole developed a model to describe the process. It was this: Deep within the Earth, naturally radioactive materials produce heat that melts rock into the substance called magma. Magma is pushed up through the seams between the midocean ridges, where it cools and spreads outward to become new oceanic crust. Meanwhile, seawater continually percolates down through the crust, where the sulfate it carries combines with iron in the crust to produce hydrogen sulfide and iron oxides. When the same seawater, now heated, is pushed back up through cracks and fissures in the crust and returned to the deep ocean, it carries hydrogen sulfide that certain bacteria find quite tasty. The same bacteria absorb oxygen dissolved in the water, and some of that oxygen combines with sulfite to become sulfate.⁸

We would seem to have come full circle, returning to the chemistry we began with. But the story is not quite over. As you may recall from chemistry class, some reactions absorb energy, while others release it. The chemical reaction that yields sulfate releases energy—which the bacteria, in lieu

sunlight and in a model of efficiency—use to drive their metabolism. From here on up, the food chain of what would come to be called hydrothermal vent communities was thought to be, roughly speaking, like that in the sunlit waters 2 kilometers above.

Corliss and Edmond understood that the water issuing from the vents was probably much diluted as it rose tens of meters through the crust, and that the real action, geochemically speaking, must be in the crust, a kilometer or two deeper down. But they would never see or study that chemistry as it was happening. Or so they thought.

Two years later, researchers who were using *Alvin* to investigate warm upwelling on the Pacific Ocean floor near the Gulf of California happened upon its source: natural chimneys of sulfide minerals, 2–3 meters high, furiously pumping water black with iron sulfide and very, very hot. So Corliss and Edmond arrived on-site, took their turn in *Alvin*, and measured the temperature of the water released by the chimneys. It was a nearly incredible 300°C. Under an atmospheric pressure at sea level, if you try to heat water gradually, it will boil away long before it reaches that temperature, and if you heat it rapidly to that temperature, it will boil explosively like (in fact, exactly like) a geyser. It is the pressure of 2 kilometers of water that keeps the chimney's water well behaved.

For Woods Hole scientists, the heat presented some challenges. They had to design and build water samplers that would work at high temperatures, and they had to be careful to keep *Alvin* a safe distance from the chimneys, as the heat might soften its Plexiglas portholes enough to implode them. But the work was exciting and welcome. In the months and years that followed, scientists from many different institutes and universities found more vents and more chimneys (they would come to be called “black smokers”) along other midocean ridges, and near all of them, a great many living organisms.*

The theory of plate tectonics had predicted hot springs in the seams between tectonic plates. In the most dramatic fashion, Corliss and Edmond's discovery of the hydrothermal vents went a long way to support that theory, and thus closed a chapter in geology. At the same time, their discovery of life that was fed and energized by hydrothermal vents opened a new chapter in biology. Like all good chapters, it provoked questions. Exactly what sorts of organisms live in these places, and in what numbers? How did they adapt to the pressure, the dark, the heat? And how exactly did they get there to begin with?

THERMOPHILES AND HYPERTHERMOPHILES

Some of these questions had been answered several years earlier by a microbiologist named Thomas Dale Brock. Brock was an assistant professor at Indiana University, developing an interest in microbial ecology—the study of the relationship of microorganisms with one another and with the environment. In the summer of 1964, on a brief sabbatical, he was among the thousands of tourists visiting Yellowstone National Park. Brock was captivated not by the bison and grizzly bears so much as by somewhat smaller organisms. He noticed distinct colors in the outflow channels of the hot springs, and when he took a closer look he was astonished to see what he later described as “pinkish gelatinous masses of material, obviously biological.”⁹

The water was decidedly hot. In fact it was nearly boiling. People had seen the pink stuff before, of course, but they did not know what Brock knew: that no microbiologist expected any microbe could live in water this hot. Microbes that live in water at temperatures between 60°C and 80°C are called “thermophiles,” and microbes that live in water with a temperature of 80°C or higher are called “hyperthermophiles.” But that is now. In 1964, few would have believed hyperthermophiles possible.

and a standard textbook recommended that researchers incubate thermophilic bacteria at temperature of 55°C or 60°C.¹⁰ The temperature Brock measured in the outflow channels was 90°C. For years, Brock had suspected that research limited to lab-grown bacteria would lead to a blinkered view, and here was his vindication. Because no one had thought bacteria could survive at temperatures much higher than 60°C, no one had bothered to look for them.

Exactly how something in plain sight might pass unnoticed by researchers was a very good question. One answer, offered by historian of science Thomas Kuhn, is that people (scientists included) see what they expect to see, and may not see what they don't expect to see. By way of example, Kuhn described an experiment in which subjects were asked to identify the color and suit of playing cards presented to them quickly and in sequence. The experiment used a trick deck. Most of its cards would be found in any deck, but a few were special, with combinations of color and suit, like a red six of spades, that do not appear in a normal deck. The test subjects, shown the cards quickly and in sequence, did not register the special cards as special, and mistakenly assigned them normal combinations of suit and color. When shown the red six of spades, for instance, many saw a red six of hearts. On the second or third run-through, some subjects began to hesitate before answering. On still more run-throughs, several became hopelessly confused, with one nearly unraveling altogether. "It didn't even look like a card that time," he said. "I don't know what color it is or whether it's a spade or a heart. I'm not even sure now what a spade looks like."¹¹ Only a few recognized the red six of spades as a red six of spades. But as soon as they did, they began to look for other special cards. Kuhn made the point that something similar happens in science. When a scientist recognizes something no one else has recognized, Kuhn wrote, there follows "a period in which conceptual categories are adjusted until the initially anomalous becomes the anticipated."¹²

In the fall of 1964, with his own conceptual categories properly adjusted, Brock anticipated the anomalous—and sought it out. He set up a laboratory in West Yellowstone and began to spend his summers exploring the boiling and superheated pools, doing a sort of microbial fishing. At particularly interesting places he would attach one end of a long string to a tree branch and the other end to a glass microscope slide, and drop the slide into the water. A few days later he would retrieve the slide and examine it. On almost every slide he found heavy bacterial growth.

Initially, other microbiologists thought Brock's discoveries too specialized and esoteric to be of wider interest. There were, after all, only so many hot springs in the world, and so there could be only so many species of thermophilic (or hyperthermophilic) bacteria living in them. Then Corliss and Edmond and their many successors found ecosystems whose basis was organisms that thrived in hot water. And the environments that they preferred, while difficult for species like *Homo sapiens* to reach, were not rare. Far from it. Mid-ocean ridges snake along the oceanic crust for tens of thousands of kilometers. By the late 1970s, microbiologists were poring over Brock's published works for ideas on how thermophilic bacteria adapted and how thermophilic ecosystems might work. And since it was easier and a lot cheaper than mounting an expedition to a mid-ocean ridge, quite a few began to visit his old haunts at Yellowstone.

Meanwhile, word of life on mid-ocean ridges was reaching all corners of academia. The life science department at most universities and colleges has a large bulletin board mounted outside the department's main office. On that bulletin board one is likely to find a notice of a forthcoming department meeting, announcements of conferences and calls for papers, as well as more personal ephemera, like a scribbled note about lost car keys. Occasionally there is a page torn from a journal on a subject that someone thought might be of general interest. Such was the case in the fall of 1977.

when it seemed that every bulletin board outside every main office of every life sciences department at every university and college—and high school too—had an article about the deep-water sulfide chimneys and the life around them.

Soon enough, biologists began to wonder whether there were other “special” cards in the deck, and many began looking. Through the 1980s and 1990s, to anyone reading the science section of a newspaper, it seemed that every other week someone had found life where (one would have thought) had no reason to be. There were heat lovers, cold lovers, pressure lovers, acid lovers, alkaline lovers, salt lovers, and even radiation lovers.* As a group they became known as *extremophiles*, a term that had been coined by R. D. MacElroy in 1974.¹³

Through much of the twentieth century, biologists classified organisms within a taxonomic system whose largest and most fundamental categories were Animalia and Plantae. Single-celled organisms like bacteria were included among the Plantae, it seemed to some, as an afterthought. In the 1960s biologists began to regard the system as inadequate, especially with respect to microorganisms, and they developed a new taxonomy in which the most fundamental divisions were five “kingdoms”: Animalia, Plantae, Fungi, Bacteria, and Protista. The kingdom of Protista, its boundaries particularly ill defined, included many organisms simply because they fit nowhere else. Certain microbiologists (among them evolutionary biologist Ernst Mayr) proposed a more fundamental division into two “empires.” Bacteria, whose cells were relatively small and lacked a nucleus, were classified as *prokaryotes* (*pro* meaning “before” and *karyote* meaning “kernel” or “nucleus”); and the other four kingdoms, whose organisms were composed of larger, nucleated cells, were classified as *eukaryotes* (*eu* meaning “true”).

In the 1960s, microbiologist Carl Woese and his colleagues began to sequence ribosomal RNA and realized that many microorganisms that had been classified as bacteria (under a light microscope they looked like bacteria) were in fact fundamentally different. The categories were redrawn yet again, this time as three “domains.” The eukaryotes were called *Eukarya*, and the prokaryotes were split into the domain *Bacteria* and the newly discovered domain *Archaea*. Woese’s taxonomy is especially pertinent to our interests here. While extremophiles include members of all three domains, most are archaea.

Of course, since they are as unlike each other as they are unlike other life, extremophiles are a group only in the sense that “all composers not Beethoven” or “all painters not Monet” are a group. Any given extremophile can be represented by a different outlying point on a bell curve, and there are bell curves for temperature, pressure, and pH. Many, like a certain species of *Acidianus* that thrives at high temperatures and low pH levels, can be represented by outlying points on *two* bell curves.¹⁴ What counts as extreme, of course, depends on who is ringing the bell. R. D. MacElroy, presumably, had a body temperature of 98.6°F and most probably a distaste for strong acids. If the *Acidianus* species were to categorize him, it would call him a “psychrophile” and an “alkaliphile”—a cold lover and an alkaline lover.¹⁵

In any case, by the 1990s the search for extremophiles had accelerated. NASA, interested in learning how organisms might adapt to harsh environments like the subsurface of Mars, funded numerous research programs—some independently, some with the National Science Foundation. In 1996 a group of biologists convened the first International Conference on Extremophiles. Within a few years researchers in the new field had established a journal and a professional society, and had published thousands of papers.

One point of agreement in all this research was that if there is a limit, an outer boundary beyond which the most extreme of extremophiles cannot pass, it was probably set by the swish, gurgle, and

drip of liquid water. It so happens that every place scientists have found life, they have also found liquid water or evidence of its presence. And almost every place they have found liquid water, they have found life.¹⁶

WATER

In a list of chemicals arranged by their molecular weight, you would expect water, with a lower weight than oxygen or carbon dioxide, to be a gas at room temperature. In fact, the only reason water is liquid hereabouts is that its molecule is polarized—the two hydrogen atoms on one side of the oxygen atom holding a slight positive charge, the oxygen atom itself holding a modest negative charge. It is an arrangement that allows water molecules to form bonds that are gentle, yet strong enough to make water bead on glass, to let it be pulled upward through a plant stem, and to endow it with surface tension—that intriguing quality by which molecules on the liquid's surface are attracted to each other more powerfully than they are to the air molecules above them or the water molecules below them.

The charged poles that pull water molecules together are the very feature that enables them to pull other molecules apart. Chemists speak of water as an unusually versatile solvent. Like the perfect dinner party host, water gently breaks apart couples (like sodium chloride) and large groups (like sugars and amino acids). Chemists also speak of water as a very good medium for diffusion. Again, like that perfect host, water provides its guests an environment in which their parts can move and mingle freely. This environment, it should be said, happens to be particularly congenial to life. Water offers protection from DNA-damaging ultraviolet radiation, and it holds heat so well that temperatures near the ocean floor are unchanging year-round. And because, by comparison with other chemicals, water stays liquid at a very wide range of temperatures (in fact, a range of 100 degrees on the scale that is based on that very liquidity), life can operate at that same wide range.

One of water's properties is at once so peculiar and so conducive to life's presumed beginnings and long-term well-being that some nineteenth-century naturalists pointed to it as evidence of intelligent design.¹⁷ If water were like most liquids, it would become denser and heavier when it froze. Ice would sink, and bodies of water in colder climes would radiate away heat and freeze solid from the bottom up. Life in those places—especially aquatic life—would have a very hard go of it. In fact, though, ice expands when it's frozen, becoming more voluminous by about 10 percent and forming a surface layer on lakes and oceans that insulates the water and organisms beneath.

As if all this congeniality weren't enough, water also uses dissolved compounds to make "microenvironments" within itself. The charged poles of water molecules lead other molecules to orient themselves side by side and facing in the same direction, some forming whole choreographed chorus lines, row after row of them, until they are best regarded as membranes. Some of these membranes develop into the microscopic bubbles that molecular chemists call *vesicles*, and whose interiors, some 4.6 billion years ago, may have sheltered the first self-replicating molecules and over time developed into cells.

Given all the virtues of water, we should not be surprised if organisms no one would call extreme go to astonishing lengths and employ ingenious strategies to get it. And they do. Spanish moss (*Tillandsia usneoides*) pulls water directly from the air; a species of kangaroo rat (*Dipodomys merriami*) draws it from metabolized food; and California redwood trees (*Sequoiadendron giganteum* and *Sequoia sempervirens*), by a means only imperfectly understood, pump it to their highest branches 100 meters above the forest floor. And once they have water, organisms no one would call extreme go to great lengths to hold it, to keep it from freezing or evaporating, to distribute it within themselves

and, where possible, to recycle it.

As for extremophiles? To acquire and retain water, they go to lengths that are, well, extreme.

FIRE AND ICE

The Celsius temperature scale uses the range at which water is liquid as its central scaffolding, but that range may be extended upward into hotter temperatures if, as we've seen, the water is kept under pressure. It may be extended downward into colder temperatures if the water is mixed with something else. Extremophiles are quite willing to exploit this wider range of temperature, and biologists are interested in the strategies they use to do it.

To appreciate the ingenuity of those strategies requires a brief refresher in biology. The *cell* is the smallest structural unit of an organism that can function independently. The cells in you and me, and in any other multicellular being, have a nucleus that contains their DNA. In the rather simpler cells of bacteria and archaea (groups to which all microbial extremophiles belong), the DNA floats freely in the semiliquid *cytoplasm*. In the cytoplasm are large molecules called *proteins* that initiate and accelerate chemical reactions in the cell and (in some cases) act as a supporting structure. The DNA, cytoplasm, and proteins are held inside a plasma membrane covered by a cell wall. The membrane protects what is inside the cell from the harsh environment outside it, and the wall prevents the cell, in certain situations, from expanding and bursting. The membrane and the proteins in the cytoplasm inside happen to be especially vulnerable to high temperatures. In water approaching boiling, the cell membrane grows more and more watery, eventually becoming too porous to do its job, while the proteins inside it are twisted, bent, or just plain broken (or as microbiologists put it, "denatured"), and so made useless.

To stay healthy in hot water, some thermophiles substitute the weaker parts of proteins with parts that are more durable and heat resistant. This is probably the method used by the hot-water record holder at present, a bacterium retrieved from a hydrothermal vent off Puget Sound. In 2000, University of Massachusetts microbiologists Derek Lovley and Kazem Kashefi had cultured the bacterium successfully and were curious about how much heat it could tolerate. They increased the temperature to 100°C, and the bacterium kept growing. The only means to still-higher temperatures that they had on hand was an autoclave, the pressurized steam-heated vessel commonly used to sterilize medical equipment—an instrument, one can't help but note, designed not to cultivate microorganisms, but to kill them. They left the bacterium cooking in the autoclave for ten hours. The bacterium reproduced at 121°C and survived for two hours at 130°C. "We were," Lovley said, "truly amazed."¹⁸

There are reports of microbes, also living near hydrothermal vents, that survive at still-higher temperatures, but collecting samples in the vicinity of hydrothermal vents is difficult, and the samples in question may have been contaminated. Still, since scientists can imagine substituting parts that would allow a cell to hold up under even higher temperatures, a confirmed finding would not be particularly surprising. As the NRC's *Limits of Organic Life* report observes, "the upper temperature limit for life is yet to be determined."¹⁹

As to the lower temperature limit? Ice threatens an organism by an act of omission, denying the organism the solvent it needs to work its chemistry. It also threatens with an act of commission: ice crystals can easily tear a cell membrane. When water inside a cell freezes, the result is, in the ominous language of one paper, "almost invariably lethal."²⁰

If water didn't mix well and life insisted on taking its drinks straight up, the coldest temperature

which an unprotected cell could survive would be 0°C, and we could learn all there was to learn about the chemistry of water in an afternoon. But as it happens, water will mix readily with any number of solutes. Stir in the right salts and you can keep water liquid at -30°C. Add some organic solvents and the temperature can go lower still. Where organisms can supply these salts and organic solvents, they will.* Some keep the juices flowing by increasing the concentration of solutes between cells; others by modifying lipids and proteins in cell membranes. Mix in an amino acid like methionine and an organic compound like ethylene glycol and you can expect that enzymes, the proteins that act as biochemical *catalysts*, speeding up reaction rates, will still do their catalyzing at a chilly -100°C.

Ideas of how organisms might adapt to mixes of water and ammonia or water and liquid methane are what get biologists (and especially *astrobiologists*, who hypothesize about extra-terrestrial life) excited about places like Saturn's moon Titan, where the warmest midday temperature might be -179°C, water ice is hard as granite, and methane, a gas in our atmosphere, is cooled to a liquid. Exactly how low, under the limbo stick of temperature, can life go? The NRC report proffers that given the right solvent, "it is possible that there is no low temperature limit for enzyme activity or cell growth."²¹

THE CHALLENGE OF SALT

It is not quite accurate to say that all extremophiles were identified after the discoveries of Corliss and Edmond. Some, including members of a group called "halophiles" (salt lovers), were found decades earlier. In the late 1930s, a graduate student named Benjamin Volcani, then studying at Hebrew University in Jerusalem, began to look for microorganisms in the Dead Sea. It was, to many, a curious pursuit. Hydrologically speaking, the Dead Sea is a closed-basin lake. In recent years, with the diversion of water from the Jordan River, its only substantial inflow, the Dead Sea has grown saltier and more alkaline. But even in the 1930s, its waters could be five times as salty as seawater, and often reached the point of saturation.²²

The threat of salt water to a cell derives from the tendency of water molecules to balance the concentration of solutes on either side of a cell membrane. Salt water outside a cell will pull water from the cytoplasm inside through the membrane, and the cytoplasm will dry up.

In the 1930s, one would have had good reason to suppose that the water in the Dead Sea was lifeless and many did. And so it came as no small surprise when Volcani found not merely a few organisms but a thriving microbial community.²³ They had solved the salt problem, as do many archaea and bacteria in brine lakes everywhere, with an "if you can't beat 'em, join 'em" strategy, keeping high concentrations of salt in their cytoplasm, and so balancing the concentration inside against the concentration outside. But enough salt inside a cell can cause other problems. It will, for instance, bond with the water molecules that normally coat proteins, stripping them of that protection and making them vulnerable to denaturing. It turns out that the proteins in the cells of salt-loving archaea and bacteria have defenses—like, for instance, charged amino acids on their surfaces that hold on to the watery coating.

THE TEST OF ACID

On a shelf in her tidy, book-lined office in Woods Hole, biologist Linda Amaral Zettler keeps a small glass vial that she purchased in a tourist shop. It contains a few milliliters of what, in another setting you might suppose to be red wine—perhaps a cabernet. In fact though, it is not quaffable, at least not by *mesophiles* like us. The liquid in the vial is a dilute acid laced with heavy metals, and it is from the

Rio Tinto, a river in southwestern Spain.

The Rio Tinto's source is an iron ore deposit—or rather, what's left of one. The site has been mined literally, since Paleolithic times, and what remains is a crater filled with water more acidic than vinegar. It is this acidity that dissolves iron, and it is the iron, oxidized by bacteria and exposed to air that gives the water its reddish color—an indication of the high concentration of metals that the river maintains for all its 600-mile length, as it winds through rust-colored hills and scrub pines to empty, finally, into the Atlantic.

For years many had assumed the river was lifeless. As Dr. Amaral Zettler will tell you, they did not look very closely.²⁴ Even without a field microscope, anyone can see films of algae on seeping walls along the river's edges and, attached to rocks beneath the surface, green filaments of algae and whitish filaments of fungi waving in the current. But perhaps more surprising is what is living in and among the films and filaments. There are amoebas, ciliates, euglenoids, and flagellates—a thriving microbial community—not as diverse as that in a freshwater pond, but far more diverse than anyone expected.

Amaral Zettler is interested in many aspects of these organisms—one of which, quite naturally, is exactly how they manage to survive. Some set up defenses at the cell membrane, mostly with additional proteins, that keep the inside at a more neutral pH and mostly free of metals. Others accumulate metals inside the cell, evidently without doing themselves serious harm. But research on the subject has barely begun, and it is probable—in fact, likely—that the microbial life in the Rio Tinto is protecting itself by other means as well.²⁵

GOING WITHOUT

Readers of a certain age will recall an advertisement found in the back pages of many comic books alongside the X-ray glasses and hovercraft plans, for “sea monkeys.” An illustration promised an underwater city bustling with miniature creatures that looked a bit like chimpanzees, if chimpanzees had spiny dorsal fins and webbed fingers and toes. It was, so we readers were led to believe, a completely self-contained alien civilization we could keep on the dresser in our bedroom. What actually arrived in the mail was less miraculous, but only slightly. It was a small foil pack containing what looked like coarse-grained paprika. If you poured it into a glass of warm salt water and held a magnifying lens to the side of the glass, you would see tiny creatures uncurl, wriggle, and swim. In fact, they were brine shrimp (*Artemia salina*).

The shrimp had survived without water through a trick shared by many organisms—including bacteria, yeasts, fungi, plants, and insects. It is a process called “anhydrobiosis,” by which cells shut down their whole metabolism and simply wait, as it were, for a rainy day. Some can wait a very long time. In the 1960s, archaeologists excavating Masada, the fortress in the Judean desert built around 70 BCE, found date seeds. Radiocarbon testing dated the seeds' shell fragments to the same period, and someone thought it might be interesting to see what would happen if the seeds were planted. Of the three, one germinated and soon grew into a healthy meter-tall plant.²⁶

These remarkable examples notwithstanding, the undisputed champions of longevity are not any particular organism, but the dormant stage in the life cycles of many bacteria, plants, algae, and fungi. They are the small, lightweight, stripped-down versions of seeds known as *spores*. As a group, spores are profligate (a single mushroom may release millions), but as individuals they are downright spartan. They keep within them little, if any, stored food, and evidently they don't need much. In 1995, scientists resuscitated *Bacillus* spores that had been trapped in amber at least 25 million years. And spores are inventive, making salt (a cell's enemy) into a shield. When salt water evaporates,

may leave deposits that have, trapped within them, tiny pockets of water called “brine inclusions” microenvironments in which spores can survive. A *Bacillus* spore has been reported revived from brine inclusions thought to be 250 million years old—older, that is, than the first mammals.²⁸

To many scientists in the late nineteenth century, spores seemed overengineered, far tougher than they needed to be; and some wondered whether they might have evolved in an environment much harsher than any on Earth. If they did, then they might explain life’s origin.

In the early nineteenth century, many natural philosophers held that organisms arise by spontaneous generation from organic matter. In 1860, French chemist and microbiologist Louis Pasteur conducted a series of experiments involving much care and many flasks and filters, and demonstrated that such a case could not be the case. Two possibilities for life’s origin on Earth remained: either life had arisen in the distant past, in the form of organisms far simpler than any in existence in 1860; or it had come from somewhere else. The second hypothesis, now termed *panspermia*, was put forth a few years after Pasteur’s work by Lord William Thomson Kelvin, who suggested that life originating on another world may have arrived on Earth via “seed-bearing meteoric stones.”²⁹

Such a trip would not be easy. Suppose it were from Mars to Earth. An organism, active or dormant, metabolizing or dormant inside a fragment of Martian rock, would have to be well positioned—not too far from a meteor strike that it would be vaporized, but near enough that it could ride the blast’s shock waves (and withstand tremendous g-forces and heat) up through the atmosphere and into interplanetary space. Once in space, it would have to survive vacuum, radiation, and extremes of temperature, and it would have to do so for years, decades, or perhaps centuries. Finally, it would have to withstand a fiery entry, along with more g-forces, into Earth’s atmosphere, ending its journey with an arrival violent enough to leave a crater.

Given spores’ well-known feats of endurance, many astro-biologists have wondered whether they might be up for the trip, and a few have devised experiments to simulate one. If you were a spore, you might regard astrobiologists as the sum of all fears. Astrobiologists have baked spores, frozen them, irradiated them, fired them from guns, and slammed them between quartz plates with explosives. And in case such simulations fell short of the rigors of actual space travel, they placed them aboard NASA’s orbiting Long Duration Exposure Facility and left them outside the spacecraft, unprotected except for a thin aluminum cover, for six years. At present, despite its advocacy by several respected scientists, panspermia lacks widespread support. Nonetheless, the upshot of all these experiments is that spores can withstand a violent launch and reentry, and that as long as they are shielded from ultraviolet radiation with a few centimeters of soil or rock, they are quite capable of surviving in space for decades—long enough for travel among planets within the Solar System. If life on Earth did come from elsewhere, it could have made the journey as a spore.

NOTHING LIKE THE SUN

Microbes collectively called “intraterrestrials” have been found several kilometers beneath Earth’s surface, making for a kind of subterranean *biosphere*.³⁰ Bacteria have been found in rock samples taken several hundred meters below the seafloor, even in places where the seafloor itself is several kilometers below sea level. No one knows how many organisms are living in this environment, but the number may be large. One recent study found between a million and a billion bacteria per gram of rock. It may be that a large proportion of all bacteria on Earth live below the floor of the sea, where their metabolisms are driven by energy from various sources (like natural radioactivity) that are utterly independent of the Sun. But even extremophiles on Earth’s surface have been discovered

exploiting unusual energy sources. One fungus was found in the water core of the Chernobyl nuclear reactor, ingeniously and fearlessly converting nuclear radiation into usable energy and managing radiation damage by keeping copies of the same chromosome in every cell.³¹

THE PRESENT

A list of extremophilic world record holders that elicits a “wow” also risks a dismissal—a assumption that they are freaks in a biological sideshow, having little to do with biologists’ larger interests. In fact, though, there are real, baseline reasons to count extremophiles as important players in the epic of life on Earth. Until the late twentieth century, many biologists supposed that all life on Earth began in the “warm little pond” that Darwin’s contemporaries favored or its more sophisticated successor, the “*prebiotic soup*” that Stanley Miller and Harold Urey tried to replicate in their famous experiments in the 1950s.* These suppositions and many others, along with a century or so of thought, were challenged when, three years after Corliss and Edmond discovered hydrothermal vent communities, Corliss and a group of colleagues published a paper arguing that life might have begun in or near a hydrothermal vent.³² Recent evidence suggests that thermophiles much like those now living near the vents may have been the ancestors of all life on Earth.³³

These discoveries come at a time when many mesophiles are being discovered and catalogued for the first time. Especially in a moment when species are being made extinct at a terrifying rate—exceeding that of the five great extinctions in the last half-billion years, and at least a hundred times faster than the normal background rate—it may come as a surprise to learn that since 2005, about 400 species of mammals have been newly identified. But this is not necessarily good news. Many were discovered precisely because, with their habitats destroyed by logging, human settlement, climate change, pesticides, invasive species, and so on, they were disturbed, made suddenly visible—and vulnerable. We are, as it were, burning down the forest and watching to see who runs out.

It is here that extremophiles bring cause for a kind of big-picture optimism. If individual organisms and whole species are fragile, then life in general is resilient, tenacious, and, in its willingness to exploit any and all environments, downright aggressive. It is also inventive. When a suitable environment does not exist, life may create one. The most extreme extremophiles are of the domain called Archaea—the domain whose members were the first life on Earth, and a billion or so years from now, when our ever-warming Sun will have baked the ground and boiled away oceans, are likely to be the last. Even now, if the worst happened and a nearby star exploded, roasting Earth with gamma rays and exterminating all life on the surface and in the upper layers of the oceans, those assemblages of bacteria and fungi living a kilometer deep would go on as if nothing had happened. In time they would colonize the surface, probably learn the trick of synthesizing sunlight, and start things all over again.

Certainly the resulting scenery wouldn’t satisfy the aesthetic of, say, nineteenth-century American landscape painters. But then again, the assemblages of bacteria and fungi probably wouldn’t much care for the aesthetic of nineteenth-century American landscape painters—or ours, for that matter. And yet they and we are distant relatives. In fact, all life we know shares certain basic features. If you could take a cell from any organism—an alga, a giant sequoia, a condor, or your second cousin—and dive through its cell membrane and into its cytoplasm, you would find precisely the same nucleic acids and proteins doing precisely the same things in precisely the same ways.³⁴

In fact, these shared features are what lead evolutionary biologists to suspect that everything that lives and has ever lived is descended from a single common ancestor, a microbe that metabolized

some 3.5–3.8 billion years ago and (luckily for us) reproduced.³⁵ You might expect that, given its role as the very origin of life on Earth, this microbe would have been granted a name evocative of grandeur and myth. But, perhaps doing an end run around cultural politics, or realizing that any name would have to be borrowed from one of the microbe’s descendants, biologists call it, somewhat prosaically, the *last universal common ancestor*, or *LUCA*.³⁶

What interests a great many biologists is that many of the features shared by all known life seem to have no “selective advantage.” In other words, it didn’t have to be this way. There were, and are, alternatives. Chemists can imagine billions of organic compounds, but life uses only about 1,500. Those working in the new field of *synthetic biology* can imagine other amino acids, other proteins, and other metabolisms (or at least parts of metabolisms) that use other processes and would work just as well, perhaps better.

Quite naturally, a question arises. Was LUCA truly universal? Might there have been, in the 4 billion years of Earth’s history, a second genesis—a moment when complex molecules gave rise to another living organism, independent of and unrelated to LUCA? Might this organism have reproduced? Might it even have established a line of descent that has endured as microscopic, single-celled Sasquatches into our own time? And if such organisms exist, since they arose from a chemistry different from that which produced LUCA, might they survive and even flourish beyond the limits of the most extreme of extremophiles?

These are profound and haunting questions, and they much occupy the thoughts of the several scientists (and one philosopher) we will meet in the next chapter.

* A few years after Corliss and Edmond discovered the community near the Galápagos, scientists returning to the site and conducting a more thorough reconnaissance discovered rows of slender white tubes with red filaments emerging from their tips—organisms now called tube worms, or *Riftia pachyptila*. In 2002 another expedition visited the site—informally termed the “Rose Garden”—and found that it had been covered with hardened lava. The midocean ridge giveth, and the midocean ridge taketh away. And, it seemeth giveth again. The same expedition found tiny tube worms and mussels the size of a fingernail—in a place they called, naturally enough, “Rosebud.” (Nevalla, “On the Seafloor”)

* Or, thermophiles and hyperthermophiles, psychrophiles or cryophiles, barophiles or piezophiles, acidophiles, alkaliphiles, halophiles, and radiophiles.

* It’s worth noting that *organic* does not mean “living or once living”; it means “denoting or relating to chemical compounds containing carbon.”

* Experiments enshrined in textbooks but whose presuppositions about the chemistry of the early Earth’s atmosphere are now largely discredited.

CHAPTER TWO

A Shadow Biosphere

Darwin was excruciatingly careful to distinguish what he knew from what he did not know, and to distinguish both from what, given the limits of biology in his day, he *could* not know. In an 1871 letter to botanist Joseph Hooker, Darwin refers to the then fashionable idea of an origin for life in “some warm little pond.” But contra many who have taken the phrase out of context, Darwin did not claim the idea as his own, and he observed later in the same letter, “It is mere rubbish thinking at present of the origin of life; one might as well think of the origin of matter.”¹

If anything, the origin of life has proved the more difficult problem. Since the mid-1920s, biologists have agreed that life is the product of complex chemistry, but other aspects of the subject have been and continue to be, vigorously debated. Many have conjectured as to its place of origin: that “warm little pond” and variations like the ocean and drying lagoons, surfaces of clays, deep-ocean hydrothermal vents, mineral surfaces of ice veins in glaciers, the pores of rocks deep within the Earth, even clouds. As mentioned in the previous chapter, some have suggested that life began elsewhere in the Solar System and was delivered to Earth via meteorite. There have been at least as many ideas as to its first form: enzymes, viruses, genes, and cells, to name a few. All these ideas have played off against the more fundamental question of life’s sheer probability, with the pendulum of informed opinion swinging on a wide arc between “improbable in the extreme” and “almost inevitable.” About the only point on which there has been general agreement is that if we could trace the ancestry of all living organisms back far enough, we would find them converging, some 3.5–3.8 billion years ago, to a single genesis. Life on Earth, so most scientists believe, began at one place and at one time.

Most scientists, but by no means all. Some suspect otherwise, and their reasoning is quite straightforward. Since, as the vast majority of biologists now believe, life is not a once-in-the-history-of-the-universe event, but a more or less inevitable by-product of physics and chemistry, it follows naturally enough that life on Earth may well have had more than one beginning. It follows further that if a second beginning had occurred under even slightly different circumstances, a different sort of life would have resulted.

This is the possibility described and explored in a 2009 article called “Signatures of a Shadow Biosphere.”² Its six authors represent, as we might expect, a rather unusual collection of expertise. Four of the six have backgrounds in the life sciences. Two of them—perhaps the two who have worked hardest to bring the article’s provocative ideas to a wider audience—are cut from a rather different disciplinary cloth. Paul Davies trained as a mathematical physicist, and as recently as the 1990s his main work was in cosmology and quantum gravity. Of late he has widened his gaze considerably, becoming more interested in fundamental questions about the nature of scientific inquiry. Carl Cleland is a member of NASA’s Astrobiology Institute and—this belying any charges that NASA lacks a wider perspective—a professor of philosophy at the University of Colorado, Boulder. She is fond of quoting Thomas Kuhn (the historian of science we met in the previous chapter) and suspect

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