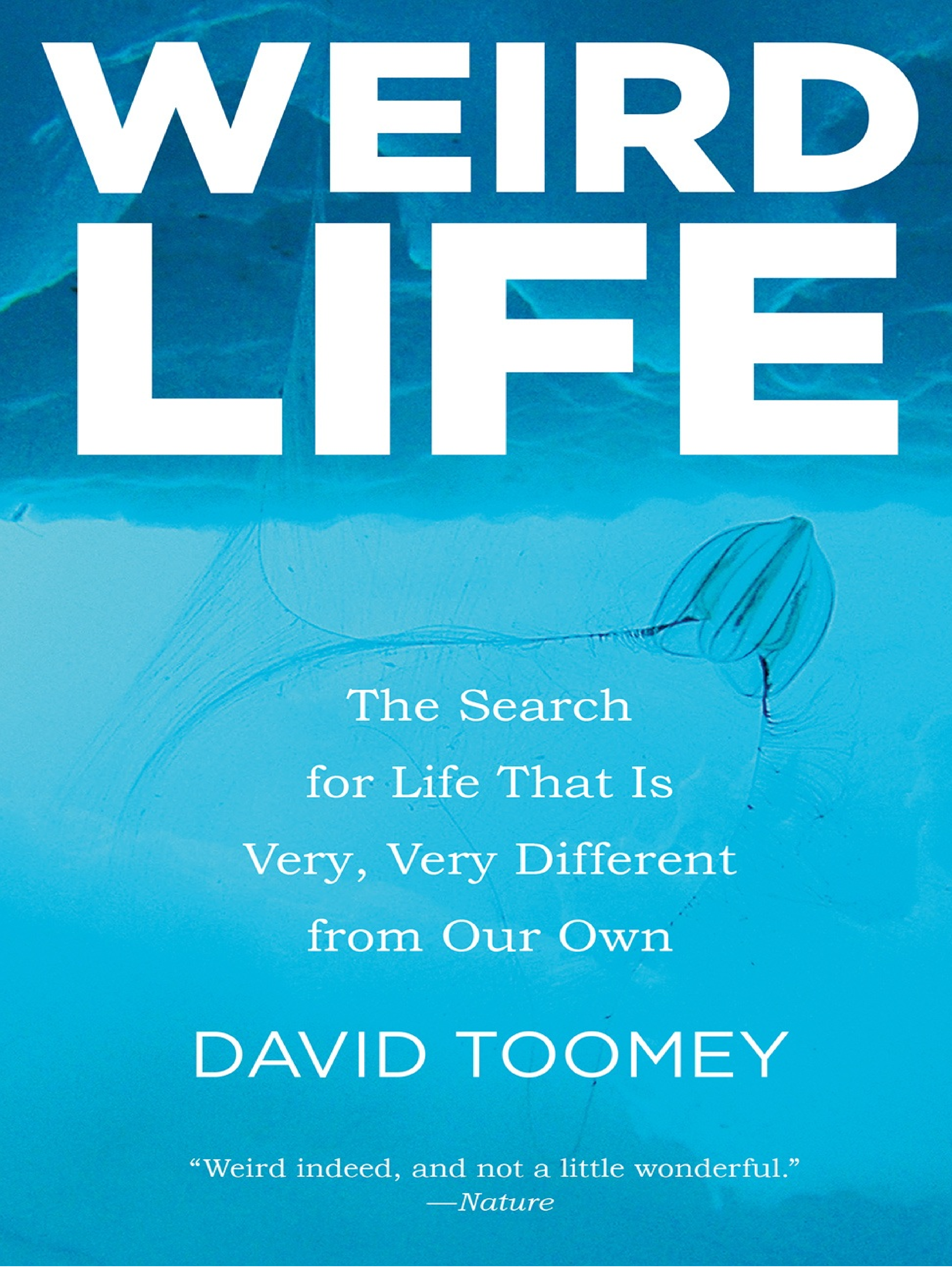

WEIRD LIFE

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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THE SEARCH FOR LIFE THAT IS VERY,
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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 boo opens as young McGrew visits his local zoo and finds its animals—a few sleepy-eyed bears and lio —uninspiring. He wishes for more exotic creatures, and so begins an extended daydream. O youthful protagonist imagines himself as the zoo's manager, releasing the bears and lions, whic shamble off, one presumes, to find more stimulating environs. Then he fantasizes himself the zoo 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. I the "Desert of Zind" he captures a ferocious sort of camel called a "Mulligatawny," and on the "Islan of Gwark" he catches a gigantic bird called a "Fizza-ma-Wizza-ma-Dill." And then he assures us th he's just warming up.

Young Gerald McGrew may be a fictional character in a children's book, but his urges resonat Humans, it seems, have always been less than satisfied with actual fauna, and so moved to inve alternatives. We all remember a few: the sphinx, the griffin, the basilisk, the phoenix. But ancie cultures created many more. Margaret Robinson's *Fictitious Beasts* (one of the most thorough a authoritative catalogues) lists several hundred, each description replete with details of behavior and many cases an instructive encounter with a god or heroic mortal.[1] To a biologist, what is strikin about this imaginary bestiary, especially in comparison with the bestiary that nature actually h produced, is its paucity. The fact is that no one knows exactly how many species reside on our plan at present, but a conservative guess is 3.6 million, and some estimates are as high as 100 million.[2] T those who prefer the real to the imaginary, it should come as good news that Robinson's work has real-world cognate. The *Encyclopedia of Life*, an effort to build an online compendium of every exta 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 abo four minutes. To get through the *Encyclopedia of Life* at the same rate you'll need six weeks. Ev 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 eac 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 wa Most are little more than portmanteaus—with, for instance, the head of one animal sewn onto t body of another. Any imaginatively sadistic schoolchild equipped with scissors and glue, you migh think, could do as well. Even the parts list is severely scaled back, derived, as it is, almost entire from the single branch of the tree of life that bears mammals, lizards, and birds. There are exceptio like "Grandmother Spider," who figures in many Native American creation myths; and the kraken, t giant squid that inhabits the imaginations of coastal dwellers on several continents. And there a some rather wondrous hybrids. The "vegetable lamb of Tartary" (*Agnus scythicus* or *Planta Tartari*

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

For most of human history, anyone seeking a little strangeness in the proportion had to be satisfie with these. Then, in the mid-seventeenth century, natural philosophers discovered another bestiar one that had two advantages over the imagined one. First, its animals were real. Second, they did n inhabit an exotic and distant country. In fact, they lived among us. And on us. A great many of ther lived *inside* us.

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

Despite such challenges, by 1664 Hooke had produced a work called *Micrographia*. Even now, in a age of high-definition television and IMAX 3D, it can be a startling experience to open the book to folded page and gently pull its leaves apart to reveal, for instance, a copperplate engraving of a fle measuring a monstrous half meter across. One of Hooke's contemporaries, Samuel Pepys, called th book the "most ingenious" he had ever read. *Micrographia* became a best seller, and many of i readers would have agreed with Hooke's observation of the flea: "the strength and beauty of this sma creature, had it no other relation at all to man, would deserve a description."[5] Still, a few criticize Hooke's pursuit of knowledge with no obvious practical application, and many more were simpl uninterested. The reason may have been that the animals discovered by Hooke and his successors we utterly unlike anything known at the time; they were perhaps *too* strange. Of course, there was anoth reason for the dis-interest: Hooke's creatures were very, very small. Then, as now, humans equat 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 or populated by animals that were as large by comparison with us as we are compared to house cat They are long vanished from the Earth, but their appeal, perhaps especially to a certain demograph of seven-year-olds, has proved enduring. Some of the reasons are obvious. Dinosaurs are strang enough to inspire wonder, but not so strange as to be wholly unfamiliar. *Tyrannosaurus rex* (a favori of the aforementioned demographic) saw through eyes not unlike our own, breathed through nostril and walked over ground.*

As the flea and *Tyrannosaurus rex* demonstrate, nature itself will outperform the uninforme imagination every time. If these creatures showed the limits of human imagination, they also enlarg it. With the discovery of microscopic and sub-microscopic life came questions about nourishmer 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 supporte 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 Alfre Russel Wallace, published *On the Origin of Species by Means of Natural Selection*. Despite attacks b religious conservatives, the book was widely read (it would see six editions in Darwin's lifetime), ar within a decade several works were published in its support. In the early years of the twentie century, biologists rediscovered Gregor Mendel's laws of heredity, and American geneticist Walte Sutton found evidence that *chromosomes* carry units of inheritance. In the 1940s, Julian Huxley ar George Gaylord Simpson consolidated natural selection and genetics, and *DNA* was found responsib for hereditary changes in bacteria. In 1953, James Watson and Francis Crick published the structure o DNA in the journal *Nature*.

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

By this time there were at least nine specialties in *biology*, the study of living organisms and li processes. Probably it shouldn't be surprising that practitioners in each specialty tended to define li in the terms of that specialty, and that they had no shared definition of the core subject at all. But wh *is* surprising is that no one thought this lack of consensus much of a problem. Taxonomists, molecul biologists, and embryologists went about their business identifying species, studying chemic 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 whe 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 o recognition, whether justified or unjustified, was not quite enough. It was about that time that NAS asked scientists to submit designs for life-detecting experiments to be carried to the planet Ma aboard the two unmanned *Viking* spacecraft. These would be the first *in situ* attempts to discover li on another world. To detect something with a miniature laboratory that would be operated remotely b a radio signal sent from a transmitter more than a million miles away was no small challenge. seemed reasonable that the task would be made easier if the "something" to be detected was proper 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 thre were designed under the assumption that life would survive in only a narrow (in fact, a rath Earthlike) range of temperatures. Depending on whom you ask, the results of that reconnaissan meant that either there was no life in the spacecrafts' vicinity or (this from one experiment) the might be some very unusual life indeed. In any case, the results did little to change larger ideas life's boundaries.

Then, in a series of discoveries in the 1980s and 1990s back on Earth, scientists found that they ha underestimated nature's ingenuity; the realm of life was (again) greater than they had dared imagin In places where no one thought life possible, organisms were not merely surviving; they were thrivin 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 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 we harvesting energy from the sunlight filtered through ice and assimilating nutrients from the wat below.

Biologists had assumed other limits as well. They had thought that organisms would tolerate only narrow range of pH levels. Then they discovered life flourishing in hot sulfur springs and growi vigorously in soda lakes. They had assumed that aquatic life would tolerate only so much salt. B they found bacteria that had adapted perfectly to saturated salt lakes. They had believed that hig levels of radiation would kill any organism. But they discovered a bacterium that, by efficient repairing broken DNA strands, could withstand radiation energies at a thousand times the level th would kill a human. They had assumed that life required a "substrate"—a surface on which i molecules could interact easily and often. But they found microbes that may be living through the 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 fe slowly from the surface, and that some survived by drawing energy from chemical reactions. Sti they assumed that all life depended—perhaps indirectly but nonetheless ultimately—on the Sun. B in 1996, a group of scientists reported the discovery, more than a mile beneath Earth's surface, assemblages of bacteria and fungi that gained all their energy from inorganic chemicals in the roc around them.

All these organisms—the bacteria in the hydrothermal vent, the algae in the Antarctic brine, th 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 mo biologists believe that they must exist, for the simple reason that there are temperatures and pressur under which the structures of organisms—cells, DNA, and proteins—will break down, no matter ho well protected. In short, life must have *ultimate* limits. If life exists outside them, it must b something other than what has been called, in that venerable phrase that can hardly be improved upo "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 w know has DNA, the same twenty or so amino acids and proteins, and a biochemistry that employs th same thousands of chemical pathways (the complex chemical reactions by which a metabolism maintained) and that uses liquid water as a solvent. It is for these reasons that biologists believe th all life we know—you, me, the flea, the megalosaurus, Charles Darwin, your neighborhood creationis and all the extremophiles—is descended from a single common ancestor. Weird life, if it exist would *not* be descended from that ancestor, and it could be weird in any number of ways. It mig have as its basis a molecule other than DNA, it might use other amino acids, or it might use a solve like ammonia or liquid methane.

Whether such substitutions are possible, or whether the fundamental features of life we know a necessary to all life, is far from clear. But it may be that some, or many, or most of those features a the products of happenstance, and that life on Earth might as easily have taken a different path, th result being organisms whose fundamental features would be utterly different from those we kno What *is* clear is that the discovery of even one example of such life would profoundly change o understanding of biology. The familiar illustration of all life we know is a great tree, its trunk splittin and splitting again into branches representing phylogenetic categories, each less fundamental a more populous than that from which it sprouted, finally ending in millions of twigs representin individual species. There have been many discoveries of new species, and recently, even a ne phylum.[7] But an example of another sort of life would mean that the tree *itself* is not unique, and th it may be only one of many, perhaps one in an entire forest. Such a discovery would be cause fo humility on our part—another demonstration that we occupy a smaller part of the universe than w now believe. It would also be cause for renewed wonder at a cosmos that is stranger and vastly rich than we now imagine.

Papers on what we now call weird life appeared sixty years ago, but they were few and scatter across disciplines. There was no overview and nothing like an ongoing discussion. The first gesture 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, t Neptune's moon Triton, to the comets. If life existed in these places, it would be radically differe 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 desola but otherwise unremarkable planet sees what he assumes is an odd rock formation. He looks away, an it moves. He looks back and realizes his mistake, and (as they say) dramatic complications ensue. B this was not science fiction. Now NASA and ESA were taking the possibility of weird life qui seriously, and making it clear that much was at stake. The discovery of extraterrestrial life—wheth it developed independently or had migrated from planet to planet via meteor, solar wind, or som other means—would have profound and lasting consequences not merely for the life sciences or eve for science in general, but for our understanding of our very place in the universe. But would w recognize life if we saw it? And if we did *not* recognize it, might we, by inattention or carelessnes destroy it?

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

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

As we'll see, in the violent early history of the Solar System, Earth and Mars traded material, som of which may have been biological. A few scientists argue that life we know may have emerged fro spores of extraterrestrial origin. For the time being I will sidestep the question of place of origin, an 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 th ancestor may have been extraterrestrial. Alternately, I will use "weird life" to mean any organism o 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 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 new retired from the face of the earth,” he wrote, “and it would not be wonderful to meet a Megalosaurus, forty feet long or so, waddli 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 Hol
Massachusetts. She is thirty-four but has an easy laugh that makes her seem even younger, and if yo
saw her jogging on a beach you might take her for a professional volleyball player. H
accomplishments in the field of oceanography and marine biology are many; she has logged nearly
year on oceangoing research vessels, and made several descents in the most famous of all researc
submarines, *Alvin*. Her main research focuses on the microbes that live in and beneath the crust of th
seafloor. They are organisms that sequester carbon, cycle chemicals, and affect the circulation o
ocean water—all of which are activities crucial to the oceans' overall health. Yet these sam
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 s
difficult to reach that if Huber hopes to study them she must use techniques from various discipline
among them geology, genetics, and molecular chemistry.

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

Lately Huber has been, in her words, "chasing seafloor eruptions." She is particularly interested
organisms that live in the Pacific, near three "seamounts" (oceanographers' term for submarin
mountains). All three seamounts are geologically active, and Huber makes periodic visits to each—o
more often, to the place on the ocean's surface several kilometers above them. The visits usually ho
surprises. In May 2009 she was on a research vessel in the western Pacific, only twelve hours out
port in Samoa, when the remote operating vehicle *Jason*, from 2 kilometers beneath them, bega
transmitting live, full-color video images of the West Mata volcano erupting. It was 3:00 a.m. on th
ship, but everyone—scientists and off-duty crew alike—was crowded into one room watching th
televised images of lava flowing, sometimes explosively, from the deepest erupting volcano anyon
had ever seen. It was, Huber said, "definitely the coolest thing I've seen on the seafloor," addin
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
battery acid, yet it contained living bacteria. There were fewer kinds than at similar sites, and so the
was a less diverse *microbial community*—this the phrase used to describe many populations
microbes living together, sharing resources, and in various ways making life better for one anothe
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 an
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 i
March 2010, she has just received an e-mail from the postdoctoral student studying under her an
doing fieldwork on a research vessel near Guam. It seems that they had set markers and moorings o
the seafloor and now couldn't find them. Huber gives a "this sort of thing happens all the time" shru
and suspects the culprit is what geologists, rather unromantically, term a "slumping event." In a
likelihood a part of the seafloor slid sideways, taking the markers and moorings with it. Just anoth
reminder, not that Huber needed reminding, that the seafloor is not the grave-quiet place that only ha
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-calle
hydrothermal vent communities, and less directly to questions that arose in the first decades of th
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 ea
coast of South America seems made to fit, jigsaw puzzle–like, into the inward-bending coast o
Africa. In 1922 a German geologist and meteorologist named Alfred Wegner went several step
further. Assembling the evidence of fossils, mineral deposits, and scars left by glaciers, he propose
that the comparison was apt. The continents *were* pieces of a puzzle, pieces that happened to be slow
drifting apart. In the decades that followed, others developed Wegner's hypothesis into a theory o
plate tectonics, which proposed that the Earth's crust is composed of plates—perhaps ten "majo
ones and as many as thirty "minor" ones. It was thought that their upper parts were brittle, their low
parts warmer and more malleable, and that some might be as much as 80 kilometers thick. Geologis
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 an
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 th
extreme, and they grow more alkaline over time. Logically, since the world's oceans have no outle
like very large closed-basin lakes, they should be very, very alkaline. Yet their pH, the measure of th
acidity or alkalinity of a solution, was between 7.5 and 8—very near the middle of the scale—and th
was the case for foaming breakers in the Florida Keys; for dark, dense water in the Mariana Trenc
and for the frigid water lapping Antarctic icebergs. It seemed clear that some process was at wor
filtering the water and maintaining the pH, and doing it everywhere. A few scientists began to suspe
undersea hot springs, and they had ideas as to their whereabouts. Hot springs on the Earth's surfac
were heated by the molten rock in nearby volcanoes; it seemed reasonable to expect that hot sprin
on the seafloor would also be near molten rock. And many thought there was molten rock in the sean
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 ne
side of the Moon. If anything, this appraisal was generous. Sonar for mapping the floor was crude, an
equipment used to measure temperatures and pressures was towed on cables behind ships. Sooner
later a cable would snag on an undersea rise, and the ship would idle its engines while a dispirite
crew pulled the equipment aboard. It usually came back wrecked—unless the cable just broke,
which case it didn't come back at all.

The United States Navy, however, had developed sophisticated techniques for mapping the ocea and by the mid-1970s the navy had begun to share them with researchers. Using these technique scientists at Woods Hole Oceanographic Institution (WHOI) implemented a three-stage method t explore a swath of seafloor. First, the research ship *Knorr* would drop transponders. Because t seafloor is uneven, they would settle at different depths. Then their positions were measured wi great precision by sonar, allowing researchers to derive a low-resolution map of the terrain. Finally, 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 seafloo 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 t eastern Pacific about 280 kilometers northeast of the Galápagos Islands. After one run over terrain 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 b WHOI) would be called into play. By the 1970s she was already something of a workhorse. In 196 she had been lost once and recovered. Two years earlier, when an air force B-52 bomber collided wit a tanker over the Mediterranean Sea and (accidentally) dropped an undetonated hydrogen bomb, *Alv* was given its moment in Cold War history and summoned to search the ocean floor off Spain. O March 17, 1966, *Alvin*'s pilots found the bomb resting on the seafloor nearly 910 meters deep. It wa raised intact. By 1977 *Alvin* had had several upgrades, but its fastest speed was a modest 4 kilomete an hour, and its lights penetrated only 15 meters. Not that any of this mattered. What *Alvin* w especially good for, and what she is still good for, is close observation. And so, when the *Knorr* foun 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 tw researchers. The researchers for this particular investigation were geologists—John Corliss of Orego State University and John Edmond of MIT. They spent most of the 2,000-meter descent peering o the Plexiglas portholes. There wasn't much to see, and even when they were a few meters above sloping seafloor, *Alvin*'s lights illuminated nothing but the hardened molten rock that geologists ca pillow basalt. It covered the sloping floor in all directions, making for a scene that, even to geologist, was not particularly remarkable. Then they noticed something about the water itself. It w shimmering like the air over a hot grill. Hurriedly, Corliss and Edmond took measurements and foun 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 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 Edmon did not know how the riotous island *ecosystem* around them was possible. They did know, howeve that *Alvin* had only five hours of power remaining, and they spent that time, Edmond would lat write, "in something close to a frenzy," measuring water temperature, conductivity, pH, and oxyge content, and taking samples of everything that *Alvin*'s mechanical arm could grab.[4] That evenin back aboard the *Knorr*, there was a small celebration. Someone had a camera and snapped photos Corliss and Edmond—young men, bleary-eyed and smiling.

In 1830, British naturalist Edward Forbes claimed that because sunlight could not penetrate deep than 600 meters, phytoplankton could not survive below that depth. Without phytoplankton, there wa no base for a food chain. It followed, reasonably enough, that the deep ocean must be sterile.[5] By t mid-twentieth century, the processes by which oceanic life sustains itself were well understoo Sunlight supplies the energy. Nutrients in the form of nitrogen and phosphorus are brought in by rive and streams and stirred up from the seafloor by upwelling currents. The floating single-celled plan called phytoplankton use the sunlight, nutrients, and carbon dioxide dissolved in the water. They a eaten by the tiny invertebrates called zooplankton that float freely throughout the seas and oth bodies of water, and the zooplankton are eaten by shrimp and other crustaceans, all the way up th food chain to the braised tuna with lemon on your dinner plate. Obviously, such processes coul operate only near the ocean surface.

In the decades that followed, however, scientists came to realize that there *was* life at great depth Fish, crabs and other organisms lived in total darkness at enormous pressures, and survived by feedi on dead and decaying matter that sank slowly from the waters above. By the mid-twentieth centur advances in nautical engineering allowed biologists to see this life firsthand. In the mid-1940s th Swiss scientist Auguste Piccard designed a vessel he called a "bathyscaphe." Unlike its predecess the bathysphere, a simple spherical pressure chamber lowered and raised by a cable, Piccard's ne design featured a float chamber for buoyancy and a separate pressure sphere for the crew. The thi bathyscaphe Piccard built was called the *Trieste*. It was sold to the United States Navy in 1957, a three years later it took Jacques Piccard (Auguste's son) and navy Lieutenant Don Walsh to th bottom of an undersea canyon called the Mariana Trench. It was there that they noticed, more than 1 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. An since recycling of decaying matter in the ocean's upper levels is fairly efficient and allows very litt to sink much lower before it is consumed, they expected those organisms to be quite hungry. So 1977, when the Woods Hole expedition's chief scientist called a marine biologist named Holge Jannasch to give him the news of a thriving community of life 2 kilometers deep, Jannasch simp 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 Corli and Edmond had happened upon a hot-spring field. Warm water was flowing up through every crac and fissure in a roughly circular patch of seafloor about 100 meters across. While *Alvin* investigate the newfound life below, scientists aboard the *Knorr* studied the water samples already returned, a found that all had a high concentration of hydrogen sulfide. That turned out to be a thread that wo together an entire *ecology*.

On land, some bacteria were known to derive energy from hydrogen sulfide through a process call chemosynthesis. They were rare, and most organisms took their energy, directly or indirectly, throug photosynthesis. But in the dark 2 kilometers deep, chemosynthesis might be the only synthes possible. Soon, researchers at Woods Hole developed a model to describe the process. It was thi Deep within the Earth, naturally radioactive materials produce heat that melts rock into the substan called magma. Magma is pushed up through the seams between the midocean ridges, where it coo and spreads outward to become new oceanic crust. Meanwhile, seawater continually percolates dov through the crust, where the sulfate it carries combines with iron in the crust to produce hydrog sulfide and iron oxides. When the same seawater, now heated, is pushed back up through cracks a fissures in the crust and returned to the deep ocean, it carries hydrogen sulfide that certain bacte find quite tasty. The same bacteria absorb oxygen dissolved in the water, and some of that oxyge 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 not quite over. As you may recall from chemistry class, some reactions absorb energy, while othe 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 cha of what would come to be called hydrothermal vent communities was thought to be, roughly speakin like that in the sunlit waters 2 kilometers above.

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

Two years later, researchers who were using *Alvin* to investigate warm upwelling on the Pacif Ocean floor near the Gulf of California happened upon its source: natural chimneys of sulfi minerals, 2–3 meters high, furiously pumping water black with iron sulfide and very, very hot. Soo Corliss and Edmond arrived on-site, took their turn in *Alvin*, and measured the temperature of th water released by the chimneys. It was a nearly incredible 300°C. Under an atmospheric pressure sea level, if you try to heat water gradually, it will boil away long before it reaches that temperatur and if you heat it rapidly to that temperature, it will boil explosively like (in fact, exactly like) 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 wat samplers that would work at high temperatures, and they had to be careful to keep *Alvin* a sa distance from the chimneys, as the heat might soften its Plexiglas portholes enough to implode the But the work was exciting and welcome. In the months and years that followed, scientists from ma different institutes and universities found more vents and more chimneys (they would come to b called “black smokers”) along other midocean ridges, and near all of them, a great many livi organisms.[*]

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

THERMOPHILES AND HYPERTHERMOPHILES

Some of these questions had been answered several years earlier by a microbiologist named Thom Dale Brock. Brock was an assistant professor at Indiana University, developing an interest 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 touris visiting Yellowstone National Park. Brock was captivated not by the bison and grizzly bears so muc as by somewhat smaller organisms. He noticed distinct colors in the outflow channels of the h springs, and when he took a closer look he was astonished to see what he later described as “pi 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, course, but they did not know what Brock knew: that no microbiologist expected any microbe cou live in water this hot. Microbes that live in water at temperatures between 60°C and 80°C are calle “thermophiles,” and microbes that live in water with a temperature of 80°C or higher are call “hyperthermophiles.” But that is now. In 1964, few would have believed hyperthermophiles possib 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° For years, Brock had suspected that research limited to lab-grown bacteria would lead to a blinker view, and here was his vindication. Because no one had thought bacteria could survive at temperatur 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 questio One answer, offered by historian of science Thomas Kuhn, is that people (scientists included) see wh they expect to see, and may not see what they don't expect to see. By way of example, Kuhn describ an experiment in which subjects were asked to identify the color and suit of playing cards presented them quickly and in sequence. The experiment used a trick deck. Most of its cards would be found any deck, but a few were special, with combinations of color and suit, like a red six of spades, that not appear in a normal deck. The test subjects, shown the cards quickly and in sequence, did n register the special cards as special, and mistakenly assigned them normal combinations of suit ar color. When shown the red six of spades, for instance, many saw a red six of hearts. On the second third run-through, some subjects began to hesitate before answering. On still more run-throug several became hopelessly confused, with one nearly unraveling altogether. "It didn't even look like 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 eve sure now what a spade looks like."[11] Only a few recognized the red six of spades *as* a red six spades. But as soon as they did, they began to look for other special cards. Kuhn made the point th something similar happens in science. When a scientist recognizes something no one else h recognized, Kuhn wrote, there follows "a period in which conceptual categories are adjusted until t initially anomalous becomes the anticipated."[12]

In the fall of 1964, with his own conceptual categories properly adjusted, Brock anticipated t anomalous—and sought it out. He set up a laboratory in West Yellowstone and began to spend hi summers exploring the boiling and superheated pools, doing a sort of microbial fishing. particularly interesting places he would attach one end of a long string to a tree branch and the oth end to a glass microscope slide, and drop the slide into the water. A few days later he would retrie 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 wider interest. There were, after all, only so many hot springs in the world, and so there could be on so many species of thermophilic (or hyperthermophilic) bacteria living in them. Then Corliss ar Edmond and their many successors found ecosystems whose basis was organisms that thrived in h water. And the environments that they preferred, while difficult for species like *Homo sapiens* reach, were not rare. Far from it. Midocean ridges snake along the oceanic crust for tens of thousan of kilometers. By the late 1970s, microbiologists were poring over Brock's published works for ide on how thermophilic bacteria adapted and how thermophilic ecosystems might work. And since it w easier and a lot cheaper than mounting an expedition to a midocean ridge, quite a few began to vis his old haunts at Yellowstone.

Meanwhile, word of life on midocean ridges was reaching all corners of academia. The life scienc department at most universities and colleges has a large bulletin board mounted outside t department's main office. On that bulletin board one is likely to find a notice of a forthcomi department meeting, announcements of conferences and calls for papers, as well as more person ephemera, like a scribbled note about lost car keys. Occasionally there is a page torn from a journal a subject that someone thought might be of general interest. Such was the case in the fall of 197

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

Soon enough, biologists began to wonder whether there were other "special" cards in the deck, a
many began looking. Through the 1980s and 1990s, to anyone reading the science section of
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 love
salt lovers, and even radiation lovers.* As a group they became known as *extremophiles*, a term th
had been coined by R. D. MacElroy in 1974.[13]

Through much of the twentieth century, biologists classified organisms within a taxonomic syste
whose largest and most fundamental categories were Animalia and Plantae. Single-celled organism
like bacteria were included among the Plantae, it seemed to some, as an afterthought. In the 196
biologists began to regard the system as inadequate, especially with respect to microorganisms, a
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 particula
ill defined, included many organisms simply because they fit nowhere else. Certain microbiologi
(among them evolutionary biologist Ernst Mayr) proposed a more fundamental division into tw
"empires." Bacteria, whose cells were relatively small and lacked a nucleus, were classified
prokaryotes (*pro* meaning "before" and *karyote* meaning "kernel" or "nucleus"); and the other fo
kingdoms, whose organisms were composed of larger, nucleated cells, were classified as *eukaryot*
(*eu* meaning "true").

In the 1960s, microbiologist Carl Woese and his colleagues began to sequence ribosomal *RNA* a
realized that many microorganisms that had been classified as bacteria (under a light microscope th
looked like bacteria) were in fact fundamentally different. The categories were redrawn yet again, th
time as three "domains." The eukaryotes were called *Eukarya*, and the prokaryotes were split into t
domain *Bacteria* and the newly discovered domain *Archaea*. Woese's taxonomy is especially pertine
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 gro
only in the sense that "all composers not Beethoven" or "all painters not Monet" are a group. A
given extremophile can be represented by a different outlying point on a bell curve, and there are be
curves for temperature, pressure, and pH. Many, like a certain species of *Acidianus* that thrives at hi
temperatures and low pH levels, can be represented by outlying points on *two* bell curves.[14] Wh
counts as extreme, of course, depends on who is ringing the bell. R. D. MacElroy, presumably, had
body temperature of 98.6°F and most probably a distaste for strong acids. If the *Acidianus* speci
were to categorize him, it would call him a "psychrophile" and an "alkaliphile"—a cold lover and
alkaline lover.[15]

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

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

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

WATER

In a list of chemicals arranged by their molecular weight, you would expect water, with a lower weig 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 oxyge atom holding a slight positive charge, the oxygen atom itself holding a modest negative charge. It an arrangement that allows water molecules to form bonds that are gentle, yet strong enough to mal water bead on glass, to let it be pulled upward through a plant stem, and to endow it with surfac tension—that intriguing quality by which molecules on the liquid's surface are attracted to each oth 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 pu other molecules apart. Chemists speak of water as an unusually versatile solvent. Like the perfe dinner party host, water gently breaks apart couples (like sodium chloride) and large groups (lil sugars and amino acids). Chemists also speak of water as a very good medium for diffusion. Aga like that perfect host, water provides its guests an environment in which their parts can move ar mingle freely. This environment, it should be said, happens to be particularly congenial to life. Wate offers protection from DNA-damaging ultraviolet radiation, and it holds heat so well th temperatures near the ocean floor are unchanging year-round. And because, by comparison with oth chemicals, water stays liquid at a very wide range of temperatures (in fact, a range of 100 degrees o 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 ar long-term well-being that some nineteenth-century naturalists pointed to it as evidence of intellige design.[17] If water were like most liquids, it would become denser and heavier when it froze. Ice wou sink, and bodies of water in colder climes would radiate away heat and freeze solid from the botto up. Life in those places—especially aquatic life—would have a very hard go of it. In fact, though, ic expands when it's frozen, becoming more voluminous by about 10 percent and forming a surface lay 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 mal "microenvironments" within itself. The charged poles of water molecules lead other molecules orient themselves side by side and facing in the same direction, some forming whole choreographe chorus lines, row after row of them, until they are best regarded as membranes. Some of the membranes develop into the microscopic bubbles that molecular chemists call *vesicles*, and who interiors, some 4.6 billion years ago, may have sheltered the first self-replicating molecules and ov time developed into cells.

Given all the virtues of water, we should not be surprised if organisms no one would call extreme g to astonishing lengths and employ ingenious strategies to get it. And they do. Spanish mo (*Tillandsia usneoides*) pulls water directly from the air; a species of kangaroo rat (*Dipodom merriami*) draws it from metabolized food; and California redwood trees (*Sequoiadendron giganteu* and *Sequoia sempervirens*), by a means only imperfectly understood, pump it to their highest branch 100 meters above the forest floor. And once they have water, organisms no one would call extreme g to great lengths to hold it, to keep it from freezing or evaporating, to distribute it within themselve 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, b that range may be extended upward into hotter temperatures if, as we've seen, the water is kept und pressure. It may be extended downward into colder temperatures if the water is mixed with somethi else. Extremophiles are quite willing to exploit this wider range of temperature, and biologists a 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 t smallest structural unit of an organism that can function independently. The cells in you and me, a in any other multicellular being, have a nucleus that contains their DNA. In the rather simpler cells bacteria and archaea (groups to which all microbial extremophiles belong), the DNA floats freely the semiliquid *cytoplasm.* In the cytoplasm are large molecules called *proteins* that initiate a accelerate chemical reactions in the cell and (in some cases) act as a supporting structure. The DN cytoplasm, and proteins are held inside a plasma membrane covered by a cell wall. The membra protects what is inside the cell from the harsh environment outside it, and the wall prevents the cell, certain situations, from expanding and bursting. The membrane and the proteins in the cytoplas inside happen to be especially vulnerable to high temperatures. In water approaching boiling, the ce membrane grows more and more watery, eventually becoming too porous to do its job, while t proteins inside it are twisted, bent, or just plain broken (or as microbiologists put it, "denatured"), a so made useless.

To stay healthy in hot water, some thermophiles substitute the weaker parts of proteins with par that are more durable and heat resistant. This is probably the method used by the hot-water reco holder at present, a bacterium retrieved from a hydrothermal vent off Puget Sound. In 200 University of Massachusetts microbiologists Derek Lovley and Kazem Kashefi had cultured t bacterium successfully and were curious about how much heat it could tolerate. They increased t temperature to 100°C, and the bacterium kept growing. The only means to still-higher temperatur that they had on hand was an autoclave, the pressurized steam–heated vessel commonly used sterilize medical equipment—an instrument, one can't help but note, designed not to cultu microorganisms, but to kill them. They left the bacterium cooking in the autoclave for ten hours. T bacterium reproduced at 121°C and survived for two hours at 130°C. "We were," Lovley said, "tru amazed."[18]

There are reports of microbes, also living near hydrothermal vents, that survive at still-high temperatures, but collecting samples in the vicinity of hydrothermal vents is difficult, and the sampl in question may have been contaminated. Still, since scientists can imagine substituting parts th would allow a cell to hold up under even higher temperatures, a confirmed finding would not particularly surprising. As the NRC's *Limits of Organic Life* report observes, "the upper temperatu 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 t organism the solvent it needs to work its chemistry. It also threatens with an act of commission: i crystals can easily tear a cell membrane. When water inside a cell freezes, the result is, in the omino 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 abo the chemistry of water in an afternoon. But as it happens, water will mix readily with any number solutes. Stir in the right salts and you can keep water liquid at –30°C. Add some organic solvents an the temperature can go lower still. Where organisms can supply these salts and organic solvents, the will.* Some keep the juices flowing by increasing the concentration of solutes between cells; other by modifying lipids and proteins in cell membranes. Mix in an amino acid like methionine and a organic compound like ethylene glycol and you can expect that enzymes, the proteins that act 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 methan are what get biologists (and especially *astrobiologists*, who hypothesize about extra-terrestrial lif 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 liqui Exactly how low, under the limbo stick of temperature, can life go? The NRC report proffers tha given the right solvent, "it is possible that there is no low temperature limit for enzyme activity or ce growth."[21]

THE CHALLENGE OF SALT

It is not quite accurate to say that all extremophiles were identified after the discoveries of Corliss an Edmond. Some, including members of a group called "halophiles" (salt lovers), were found decad 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 curiou pursuit. Hydrologically speaking, the Dead Sea is a closed-basin lake. In recent years, with th diversion of water from the Jordan River, its only substantial inflow, the Dead Sea has grown saltie and more alkaline. But even in the 1930s, its waters could be five times as salty as seawater, and ofte reached the point of saturation.[22]

The threat of salt water to a cell derives from the tendency of water molecules to balance th concentration of solutes on either side of a cell membrane. Salt water outside a cell will pull wat 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 lifeles and many did. And so it came as no small surprise when Volcani found not merely a few organism but a thriving microbial community.[23] They had solved the salt problem, as do many archaea an bacteria in brine lakes everywhere, with an "if you can't beat 'em, join 'em" strategy, keeping hig concentrations of salt in their cytoplasm, and so balancing the concentration inside against th concentration outside. But enough salt inside a cell can cause other problems. It will, for instanc bond with the water molecules that normally coat proteins, stripping them of that protection an making them vulnerable to denaturing. It turns out that the proteins in the cells of salt-loving archae and bacteria have defenses—like, for instance, charged amino acids on their surfaces that hold on 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 sma glass vial that she purchased in a tourist shop. It contains a few milliliters of what, in another settin you might suppose to be red wine—perhaps a cabernet. In fact though, it is not quaffable, at least n by *mesophiles* like us. The liquid in the vial is a dilute acid laced with heavy metals, and it is from th

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 mine~~ literally, since Paleolithic times, and what remains is a crater filled with water more acidic tha vinegar. It is this acidity that dissolves iron, and it is the iron, oxidized by bacteria and exposed to ai that gives the water its reddish color—an indication of the high concentration of metals that the riv maintains for all its 600-mile length, as it winds through rust-colored hills and scrub pines to empt finally, into the Atlantic.

For years many had assumed the river was lifeless. As Dr. Amaral Zettler will tell you, they did no look very closely.[24] Even without a field microscope, anyone can see films of algae on seeping wal along the river's edges and, attached to rocks beneath the surface, green filaments of algae and whitis filaments of fungi waving in the current. But perhaps more surprising is what is living in and amo the films and filaments. There are amoebas, ciliates, euglenoids, and flagellates—a thriving microbi 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, exactly how they manage to survive. Some set up defenses at the cell membrane, mostly with add proteins, that keep the inside at a more neutral pH and mostly free of metals. Others accumula metals inside the cell, evidently without doing themselves serious harm. But research on the subje has barely begun, and it is probable—in fact, likely—that the microbial life in the Rio Tinto 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 book alongside the X-ray glasses and hovercraft plans, for "sea monkeys." An illustration promised underwater city bustling with miniature creatures that looked a bit like chimpanzees, if chimpanze had spiny dorsal fins and webbed fingers and toes. It was, so we readers were led to believe, completely self-contained alien civilization we could keep on the dresser in our bedroom. Wh 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 wat and held a magnifying lens to the side of the glass, you would see tiny creatures uncurl, wriggle, a swim. In fact, they were brine shrimp (*Artemia salina*).

The shrimp had survived without water through a trick shared by many organisms—includi bacteria, yeasts, fungi, plants, and insects. It is a process called "anhydrobiosis," by which cells sh down their whole metabolism and simply wait, as it were, for a rainy day. Some can wait a very lo time. In the 1960s, archaeologists excavating Masada, the fortress in the Judean desert built around 3 BCE, found date seeds. Radiocarbon testing dated the seeds' shell fragments to the same period, a someone thought it might be interesting to see what would happen if the seeds were planted. Of t three, one germinated and soon grew into a healthy meter-tall plant.[26]

These remarkable examples notwithstanding, the undisputed champions of longevity are not a particular organism, but the dormant stage in the life cycles of many bacteria, plants, algae, and fung They are the small, lightweight, stripped-down versions of seeds known as *spores*. As a group, spor are profligate (a single mushroom may release millions), but as individuals they are downrig spartan. They keep within them little, if any, stored food, and evidently they don't need much. 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 fro 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 tha they needed to be; and some wondered whether they might have evolved in an environment muc 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 spontaneou generation from organic matter. In 1860, French chemist and microbiologist Louis Pasteur conducte a series of experiments involving much care and many flasks and filters, and demonstrated that suc could not be the case. Two possibilities for life's origin on Earth remained: either life had arisen in th distant past, in the form of organisms far simpler than any in existence in 1860; or it had come fro somewhere else. The second hypothesis, now termed *panspermia*, was put forth a few years aft Pasteur's work by Lord William Thomson Kelvin, who suggested that life originating on anoth 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, activel metabolizing or dormant inside a fragment of Martian rock, would have to be well positioned—not s near a meteor strike that it would be vaporized, but near enough that it could ride the blast's shoc waves (and withstand tremendous g-forces and heat) up through the atmosphere and in interplanetary space. Once in space, it would have to survive vacuum, radiation, and extremes temperature, and it would have to do so for years, decades, or perhaps centuries. Finally, it would hav to withstand a fiery entry, along with more g-forces, into Earth's atmosphere, ending its journey wi an arrival violent enough to leave a crater.

Given spores' well-known feats of endurance, many astro-biologists have wondered whether the might be up for the trip, and a few have devised experiments to simulate one. If you were a spore, yo might regard astrobiologists as the sum of all fears. Astrobiologists have baked spores, frozen ther irradiated them, fired them from guns, and slammed them between quartz plates with explosives. An in case such simulations fell short of the rigors of actual space travel, they placed them aboa NASA's orbiting Long Duration Exposure Facility and left them outside the spacecraft, unprotecte except for a thin aluminum cover, for six years. At present, despite its advocacy by several respecte scientists, panspermia lacks widespread support. Nonetheless, the upshot of all these experiments that spores can withstand a violent launch and reentry, and that as long as they are shielded fro ultraviolet radiation with a few centimeters of soil or rock, they are quite capable of surviving in spac for decades—long enough for travel among planets within the Solar System. If life on Earth did com 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 surface, making for a kind of subterranean *biosphere*.[30] Bacteria have been found in rock sampl taken several hundred meters below the seafloor, even in places where the seafloor itself is sever kilometers below sea level. No one knows how many organisms are living in this environment, but th number may be large. One recent study found between a million and a billion bacteria per gram rock. It may be that a large proportion of all bacteria on Earth live below the floor of the sea, whe their metabolisms are driven by energy from various sources (like natural radioactivity) that a utterly independent of the Sun. But even extremophiles on Earth's surface have been discovere exploiting unusual energy sources. One fungus was found in the water core of the Chernobyl nucle ~~reactor, ingeniously and fearlessly converting nuclear radiation into usable energy and managi~~ 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’ larg interests. In fact, though, there are real, baseline reasons to count extremophiles as important playe in the epic of life on Earth. Until the late twentieth century, many biologists supposed that all life o Earth began in the “warm little pond” that Darwin’s contemporaries favored or its more sophisticate successor, the “*prebiotic* soup” that Stanley Miller and Harold Urey tried to replicate in their famo experiments in the 1950s.[*] These suppositions and many others, along with a century or so of though were challenged when, three years after Corliss and Edmond discovered hydrothermal ve communities, Corliss and a group of colleagues published a paper arguing that life might have beg in or near a hydrothermal vent.[32] Recent evidence suggests that thermophiles much like those no 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 f 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 tim faster than the normal background rate—it may come as a surprise to learn that since 2005, about 4 species of mammals have been newly identified. But this is not necessarily good news. Many we discovered precisely because, with their habitats destroyed by logging, human settlement, clima change, pesticides, invasive species, and so on, they were disturbed, made suddenly visible—a 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 organism and whole species are fragile, then life in general is resilient, tenacious, and, in its willingness exploit any and all environments, downright aggressive. It is also inventive. When a suitab environment does not exist, life may create one. The most extreme extremophiles are of the doma called Archaea—the domain whose members were the first life on Earth, and a billion or so yea from now, when our ever-warming Sun will have baked the ground and boiled away oceans, are like to be the last. Even now, if the worst happened and a nearby star exploded, roasting Earth with gamm rays and exterminating all life on the surface and in the upper layers of the oceans, those assembla of bacteria and fungi living a kilometer deep would go on as if nothing had happened. In time th would colonize the surface, probably learn the trick of synthesizing sunlight, and start things all ov again.

Certainly the resulting scenery wouldn’t satisfy the aesthetic of, say, nineteenth-century Americ landscape painters. But then again, the assemblages of bacteria and fungi probably wouldn’t mu care for the aesthetic of nineteenth-century American landscape painters—or ours, for that matte And yet they and we are distant relatives. In fact, all life we know shares certain basic features. If yo could take a cell from any organism—an alga, a giant sequoia, a condor, or your second cousin—a dive through its cell membrane and into its cytoplasm, you would find precisely the same nucle 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 th lives and has ever lived is descended from a single common ancestor, a microbe that metaboliz some 3.5–3.8 billion years ago and (luckily for us) reproduced.[35] You might expect that, given its ro as the very origin of life on Earth, this microbe would have been granted a name evocative of grande and myth. But, perhaps doing an end run around cultural politics, or realizing that any name wou have to be borrowed from one of the microbe's descendants, biologists call it, somewhat prosaicall 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 have no "selective advantage." In other words, it didn't have to be this way. There were, and ar alternatives. Chemists can imagine billions of organic compounds, but life uses only about 1,50 Those working in the new field of *synthetic biology* can imagine other amino acids, other proteins, a other metabolisms (or at least parts of metabolisms) that use other processes and would work just 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 another living organism, independent of and unrelated to LUCA? Might this organism have th reproduced? Might it even have established a line of descent that has endured as microscopic, singl celled Sasquatches into our own time? And if such organisms exist, since they arose from a chemist different from that which produced LUCA, might they survive and even flourish beyond the limits the most extreme of extremophiles?

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

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

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

* It's worth noting that *organic* does not mean "living or once living"; it means "denoting or relating to chemical compou containing carbon."

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

CHAPTER TWO

A Shadow Biosphere

Darwin was excruciatingly careful to distinguish what he knew from what he did not know, and t
distinguish both from what, given the limits of biology in his day, he *could* not know. In an 1871 lett
to botanist Joseph Hooker, Darwin refers to the then fashionable idea of an origin for life in "som
warm little pond." But contra many who have taken the phrase out of context, Darwin did not clai
the idea as his own, and he observed later in the same letter, "It is mere rubbish thinking at present o
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, biologis
have agreed that life is the product of complex chemistry, but other aspects of the subject have bee
and continue to be, vigorously debated. Many have conjectured as to its place of origin: that "war
little pond" and variations like the ocean and drying lagoons, surfaces of clays, deep-ocea
hydrothermal vents, mineral surfaces of ice veins in glaciers, the pores of rocks deep within the Eart
even clouds. As mentioned in the previous chapter, some have suggested that life began elsewhere i
the Solar System and was delivered to Earth via meteorite. There have been at least as many ideas
to its first form: enzymes, viruses, genes, and cells, to name a few. All these ideas have played o
against the more fundamental question of life's sheer probability, with the pendulum of informe
opinion swinging on a wide arc between "improbable in the extreme" and "almost inevitable." Abo
the only point on which there has been general agreement is that if we could trace the ancestry of a
living organisms back far enough, we would find them converging, some 3.5–3.8 billion years ago,
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 qui
straightforward. Since, as the vast majority of biologists now believe, life is not a once-in-the-histor
of-the-universe event, but a more or less inevitable by-product of physics and chemistry, it follow
naturally enough that life on Earth may well have had more than one beginning. It follows further th
if a second beginning had occurred under even slightly different circumstances, a different sort of li
would have resulted.

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