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 out 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, at 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. Carol 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 suspects that many scientists miss opportunities because they don't think outside the box Kuhn calls the "reigning paradigm." It is Cleland, along with microbiologist Shelley Copely, who coined the phrase *shadow biosphere*—a provocative and slightly unsettling reference to a hypothetical biosphere of microbial weird life that, like the realm of fairies and elves just beyond the hedgerow, may or may not impinge on our own.

Davies, Cleland, and the other authors of the article are excited by this possibility for two reasons. First, the discovery of such life would make it possible for biologists, by comparing the differences and commonalities of two examples of life, to begin to discover universal laws of biology much as physicists since Newton have discovered universal laws of physics. As a science, biology would have fully matured. Second, and more profoundly, the discovery of such life would settle the debate over life's probability once and for all. It would mean that life in the universe is common and may arise anywhere conditions are right. Not incidentally, such a discovery would ripple far beyond biology into all realms of human experience, altering forever our understanding of our place in the universe.

But we're getting ahead of ourselves. If a shadow biosphere of weird life exists, it would be prudent, before confronting questions of its larger meaning, to ask where and how it might have begun.

A SECOND GENESIS

The scarred and battered face of Earth's Moon is the visible legacy of the violence of the early Solar System, a time some 4 billion years ago when asteroids and comets routinely struck all its larger worlds, including a molten, slowly cooling Earth. Heat and radioactivity from the planet's core sent lava through cracks in the newly formed crust, and as the surface cooled, steam from the atmosphere condensed and fell as rains that, lasting for millennia, created the planet's first, shallow oceans. Such an environment would seem inhospitable to life, yet the most necessary ingredients were there: complex carbon-based molecules and liquid water. Indeed, most scientists believe that this is the environment in which life gained its first foothold.

Almost all familiar life builds its proteins from the same twenty *amino acids*—the molecules that biology textbooks call life's "building blocks."* What's interesting is that an organism would enjoy no particular advantage by limiting itself to these twenty, and many others might work as well. It seems that in its first incarnations, familiar life used the amino acids it used for no better reason than that they were available and nearby. In another part of the early Earth (and Earth, it is worth remembering, is a big place—still bigger if you're a few complex organic molecules edging toward replication and self-organization), other amino acids would be available. And another set of complex organic molecules edging toward replication and self-

* The equivocation in that word "almost" derives from the fact that scientists actually know of twenty-*two* naturally occurring amino acids on Earth. The genetic code of certain organisms can include selenocysteine and pyrrolysine, although the latter has been found so far in only one organism—an archaean called *Methanosarcina barkeri*.

organization might use them—the result being a second genesis, of another sort of life.

In 1988, Caltech geologists Kevin Maher and David Stevenson suggested that the standard picture of life's beginning was too simple.[3] Their point was that conditions suitable for life may have lasted many millions of years; there was world enough and time for many beginnings—but perhaps no more than beginnings. The reason for that last qualification is that the era in Earth's history when life began overlapped with periods of "heavy bombardment" by meteors. Every so often—on average once in a half-million years—an unusually large meteorite—say, the size of Manhattan Island—would strike with such force that the oceans would boil, the atmosphere would be superheated, and the planet would be rendered all but sterile. The time between each of these armageddons might be just enough for life to begin all over again. But if one beginning during any particular respite is unlikely, two beginnings are improbable in the extreme. And for this reason we might conclude that there is little chance that at any given time two forms of life coexisted. We might conclude this, that is, except for the fact that no particular sterilization would be complete. After all, familiar life today survives and flourishes on the ocean floor and deep underground—both places well protected from any unpleasantness nearer the Earth's surface. A robust sort of primitive organism might have done likewise.

Sheltered locales on and in Earth are not the only places such an organism might have weathered the storm. Davies has suggested another, rather more distant, refuge. A meteor striking Earth with sufficient force might launch fragments of rock into orbit around the Sun. Some meteors might hold microbes or spores that could lie dormant for thousands or even millions of years, until the moment when the orbit of the rock fragments and

the orbit of Earth happened to intersect, and the fragments would fall back to Earth. Some would split open on impact, and their microbial passengers—any that survived, that is—would wake to a world once again fit for life, and perhaps already harboring another kind of life, one that had appeared in the half-million years during which they were away. Like Homer's Odysseus, the microbes would have returned home after a voyage of many years, to find strangers living there. It would be a space odyssey on a microbial scale—and an interplanetary one.

As mentioned earlier, life on Earth might not only have returned from somewhere else. It might have *begun* somewhere else. Four billion years ago, the planet Mars had a thick atmosphere of carbon dioxide, with rainfall, and streams and rivers of liquid water coursing through valleys and emptying into lakes and shallow seas. In short, it was a congenial abode for life. Like Earth of the period, Mars was also pummeled with meteors, and some struck with enough force to launch rock fragments into orbit around the Sun. After thousands or millions of years, some of the fragments intersected Earth's orbit and fell to Earth. In fact, scientists have found at least twenty-eight of them, one of which is ALH84001, made famous in 1996 when David McKay, chief scientist for astrobiology at NASA's Johnson Space Center, and his research group suggested that it bore evidence of life. Although their conclusions remain controversial, it seems clear that early in their history, Earth and Mars traded material, and some of that material may have contained microbes. Davies and others believe it barely possible that life on Earth—familiar, weird, or both—has a Martian ancestry.

None of these ideas are proof that weird life, let alone a shadow biosphere of weird life, exists. But collectively, they make a case that weird life had ample time to arise on Earth and several means by which to do it. Suppose then, that it did arise. An obvious question presents itself: Wouldn't we have noticed by now? And if it were microbial, wouldn't microbiologists have noticed? The answer, interestingly enough, is: not necessarily.

WHAT WE DON'T KNOW

Those of us who take our science news from *Discover* magazine and nature shows are regularly and properly astounded by what biologists and microbiologists know. If we were to learn what they *don't* know, we might be just as astounded, for what they don't know is a great deal. Take, for example, the answer to the straightforward question, How many species are there? The difficulty here is simply that there is no reliable way to determine that number, or even to estimate it, except perhaps to replicate work performed in 1981 by Terry Erwin of the Smithsonian Institution.

Erwin wanted a census of the number of the world's arthropod species—insects, spiders, crustaceans, centipedes, and the like. He and his team arranged a grid of specimen bottles, with 1-meter-wide funnels affixed to each, beneath a tree in Panama. With the air calm, they sprayed insecticide into the canopy, and some hours later they collected and began to classify the thousands of arthropods that had fallen through the funnels and into the bottles. Erwin counted 163 species of beetles known to live exclusively in the species of tree they had fallen out of, multiplied that number by the number of tropical tree species known, and concluded that beetle species numbered more than 8 million (thus incidentally supplying quantitative evidence for British geneticist J. B. S. Haldane's possibly apocryphal remark that the Creator must have "an inordinate fondness for beetles"[4]). Since

beetles are known to represent 40 percent of all arthropods, Erwin assumed the same proportion in the tree whose denizens were under study, and after a number of other calculated guesses, he concluded that the number of arthropod species worldwide might be as high as 30 million.[5] But no one, including Erwin, thinks this number definitive, and other estimates vary wildly.

Bear in mind, too, that this is only what we don't know about just one phylum. Our ignorance of the rest of the natural world is proportionately greater. In 2002 the famed entomologist Edward O. Wilson estimated that 1.5–1.8 million species have been identified and catalogued, but well-reasoned guesses of the actual number lay within a stunningly wide range: 3.6–100 million.[6] The full meaning of these numbers is so dumbfounding as to bear restating: for every species known to science, there is at least one that is unknown, and there may be as many as fifty.

Since Erwin's work, several international programs have begun to catalogue biodiversity. The Census of Marine Life, a decade-long project to make a comprehensive tally of life in Earth's oceans, found 5,000 previously unknown species, including an animal that lives without oxygen, several species believed to be extinct since the Jurassic period, and 600-year-old tube worms. The ongoing International Barcode of Life project identifies species with only a snippet of their DNA, and has so far assigned bar codes to more than 100,000 species. Coordinated with both projects and with several zoological organizations is the *Encyclopedia of Life* (mentioned earlier), now at half a million pages and growing.

Of species still undiscovered, it is possible that some are quite large. As recently as the mid-1990s, scientists were astonished to discover a 200-pound animal inhabiting the mountains shared by Vietnam and Laos. It looks part antelope and part cow but, now classified as the only member of the genus *Pseudoryx*, is neither. Most unknown species, though, are likely to be small—and many are no doubt microscopic. The 1989 edition of Bergey's *Manual of Systematic Bacteriology* lists roughly 4,000 species of bacteria,[7] but microbiologists, using several ingenious and indirect measurements, have inferred that the true number may be in the millions.

Our ignorance of the microbial realm is disquieting—or should be—not merely because there is so much of it (microbes compose as much as 80 percent of the Earth's biomass and 10 percent of your dry body weight), but because it is the realm from which our own "macrobial" realm originated and upon which it still depends. Microorganisms act as the basis of all food chains and work to regulate the chemistry of Earth's atmosphere and oceans. In fact, if the *Gaia hypothesis* of British inventor and scientist James Lovelock and American biologist Lynn Margulis has any validity, then Earth's climate has for billions of years been held in delicate equilibrium by oceanic phytoplankton and other microorganisms working, one must note, without committees, treaties, or international protocols. Their other achievements are similarly impressive. They originated all the chemical systems upon which life depends, systems we cannot yet replicate and do not fully understand. And they have adapted to the most extreme of Earth's environments—environments in which we, without artificial means anyway, could not survive. Microbes were the first organisms on Earth, and given their record of success, they will surely be the last.

The reason we have so little knowledge of the microbial world lies in the limitations of the instruments and techniques we have available to explore it. Under a microscope, that most time-honored of scientific tools, a given species from the domain

Archaea and a given species from the domain Bacteria may be indistinguishable, even though they have less in common with each other than you have with, say, a soft-shell crab. Most bacteria and archaea look like spheres or rods. Microbiologists can enhance the view and identify parts of any given cell with "staining," but the parts might represent only some differences, and not necessarily the most important or fundamental ones.

Microbiologists who want to study a microbe thoroughly and over time will "culture" it—that is, introduce a sample of the microbe to nutrients in standard culture dishes, and wait until the sample proliferates into a colony containing enough individual microbes that they can be sorted and analyzed. This is not as easy as you might expect. While certain species, most famously *Escherichia coli*, grow so readily that laboratory biologists call them "weeds," the fact is that most single-celled organisms don't survive long in captivity. Many a microbe that thrives in a puddle or pond, when carefully removed, carefully transported, and carefully placed in a culture dish, will shrivel up and die. To a nonscientist, it may come as a shock to learn that biologists have been able to culture less than 1 percent of the microbes they have seen, as it were, in the wild.[8]

Not that they know all that much about the wild. With humility that one can only call admirable, the NRC report of 2007 notes, "It is clear that little or nothing is known of the physiological diversity of most microorganisms in most Earth environments."[9] This includes environments that are nearby. As Wilson observes, a pinch of soil from any forest floor, no more than can be held between thumb and forefinger, is likely to contain thousands of bacterial species, many of them unknown.[10]

All this is by way of saying that the fact that we have not found microbial weird life should not lead us to conclude that it doesn't exist. As English Astronomer Royal Martin Rees observed, with regard to another scientific mystery, "Absence of evidence is not evidence of absence."[11] Or is it?

I add a dollop of doubt because we might easily imagine a second objection to the notion of weird life. Familiar life is successful, as mentioned earlier, because it is resilient, tenacious, aggressive, and inventive. Suppose that at some moment in the roughly 4-billion-year reign of familiar life, a sort of weird life *did* emerge. Might we assume that it would have lost any and all competition for resources, and that almost immediately after its appearance, familiar life would have pushed it into extinction? The answer, again, is: not necessarily. According to Davies, Cleland, and their colleagues, there are at least three ways weird life might have managed, and might manage still: as ecologically separate from familiar life, ecologically integrated with it, or biochemically integrated with it.

THREE TYPES OF SHADOW BIOSPHERE

One way weird life could manage is by moving into places that no familiar life, not even extremophiles, wants. There are many such places—the core of Chile's Atacama Desert,[12] ice sheet plateaus, hydrothermal vents with temperatures above 400°C, and high-brine liquid water at temperatures below −30°C. Weird life in any of these places would likely be part of a biosphere *ecologically separate* from our own—and these are phenomena known to exist. Since 1990, scientists have discovered several ecosystems of extreme familiar life that are separated from the rest of the biosphere. There is a microbial community beneath the Columbia River in Washington State composed of bacteria that live inside basalt rock, another in the Twin Falls area of Idaho, still

another near a gold mine in South Africa.[13] Each is remarkable for its source of energy: chemosynthesis in the first two cases, and radioactive decay in the third.

There is also the possibility that weird microbes, while greatly outnumbered by familiar microbes, are living among them. Molecular biologist Mitch Sogin, a coauthor of the 2007 NRC report, called the diversity of most microbial communities "staggering," and noted that most of the diversity was owed to a small number of individual microbes.[14] In other words, few microbes of each species, but an enormous number of species nonetheless. It is possible that weird life is present and unaccounted for in many microbial communities, keeping its profile low and, since it is weird, consuming what no one else wants and excreting what no one else is bothered by. Such weird life would compose a biosphere *ecologically integrated* with our own.

Finally, there is the possibility—this perhaps the strangest of all—of weird microbes and familiar microbes in *symbiotic* relations that benefit both, trading chemical compounds, enzymes, or even genes. Symbiotic relations in the microbial realm have a long history—a history demonstrating that, contra ideas of nature as "red of tooth and claw," there is as much cooperation as competition, and perhaps a good deal more.* Consider the strange case of mitochondria, the *organelles* that perform respiration and generate chemical energy. It is thought that some 3 billion years ago they were oxygen-respiring purple bacteria and microbial nomads, finding comfort and sustenance where they

* The idea of cooperation between species was (of course) not lost on Darwin, who noted, "A flower and a bee might slowly become, either simultaneously or one after the other, modified and adapted in the most perfect manner to each other, by the continued preservation of individuals presenting mutual and slightly favourable deviations of structure." (*Origin of Species*, 85)

could, and otherwise making do in a harsh world. The, one or several of them found refuge in the warm, wet, pH-balanced interior of a cell, and took up permanent residence. Others followed, and achieving survival more by snuggle than struggle, host and guest eventually negotiated terms. The cell provided the bacteria protection, and the bacteria supplied the cell with oxygen-derived energy and disposed of its waste. In the fullness of time, the arrangement developed into a codependency so complete that today, the cells in your body would die without the mitochondria inside them.

If weird microbes exist, it is possible they've established similar arrangements with familiar microbes. They would comprise a biosphere *biochemically integrated* with our own. If ecologically separate weird life is the person you'll never meet, and ecologically integrated weird life is that utterly silent and all but invisible boarder, then biochemically integrated weird life is the roommate who shares your toothbrush, borrows a twenty from your wallet and forgets she did it, but at regular intervals thoughtfully leaves a bouquet of flowers and a bottle of wine on the kitchen table.

At least in theory, there is no good reason to suppose that weird life doesn't exist on Earth. Suppose, then, that it does. The prospect is exciting for all the same reasons that the prospect of life on other worlds is exciting—perhaps more so, for the simple reason that weird life on Earth might be easier to find.

The search for life on other worlds—which began in earnest with recommendations from NASA subcommittees in the 1960s—has proved more challenging than many had anticipated, and it is unlikely to yield results anytime soon. The difficulty lies in the distance between researchers and their possible subject. Earthbound astronomers using long-range detection techniques like spectrometry can examine the atmospheres of planets and

moons in our Solar System—and when conditions are right, some planets in other systems—for chemical compounds commonly called "biosignatures" that may have been produced by living organisms. But without on-site study by astronaut-scientists, sample-return missions, or at the very least, sophisticated unmanned probes, they can't know whether such compounds are true biosignatures or merely the product of an exotic chemistry.* To date, the only *in situ* search for life elsewhere came in NASA's *Viking* missions—with results that were inconclusive. The next-generation Mars Science Laboratory, which began its journey to the Red Planet in late 2011, is designed to answer questions about how well the Martian environment is suited to life, not to seek life directly. At the time of this writing, missions to Mars and elsewhere designed specifically to look for weird life are distant prospects at best.

By way of contrast—and this is a point Davies and Cleland make rather tirelessly—a systematic search for weird life on Earth could begin immediately and at a far lower cost. The only real question is how best to go about it.

SEEKING WEIRD LIFE ON EARTH

In a search for weird life on Earth, the standard tools and techniques for identifying microbes are unlikely to be of much help. The similar appearance of archaea and bacteria under a microscope suggests that their shapes—spheres and rods—have real evolutionary advantages, and we can expect that weird microbes

* The same uncertainty surrounds the detection of trace amounts of methane in Mars's atmosphere, which may indicate life but may also be produced by a geochemical process. (Tenenbaum, "Making Sense of Mars Methane")

will look much the same. Staining can highlight gross features of cells, but it can miss smaller ones, and these might be the very features that make the cells weird. Attempts to culture weird microbes would be especially challenging. Microbiologists trying to culture familiar microbes must make an educated guess as to the microbes' needs in the way of temperature, humidity, and nutrients. As to the needs of weird life, they might have no idea. It is true that there is a relatively new tool used to identify microbes, called "DNA amplification." But it works only if the DNA in question uses the sugars and bases of familiar life. It also works, of course, only with a microbe that has already been isolated. It would be of little use in distinguishing a weird-life microbe from the thousands of species of familiar life in that pinch of soil from the forest floor.

For that, Davies proposes a general rule of thumb: the more fundamental an organism's differences from familiar life, the greater its chances of being weird. For instance, if an organism uses a different amino acid, it is probably an unusual form of familiar life. But if it uses ammonia (not water) as a solvent, or silicon (not carbon) as a binding molecule, it is almost certainly weird. The hard calls would be in the middle, and one reason to expect some in the middle is a phenomenon called *convergent evolution*. This is the process by which two species respond to the same environmental challenge and take advantage of the same environmental circumstance by developing features that are similar—and in some cases identical.

The eyes of humans and octopi are an oft-cited but nonetheless remarkable example. Even in their details the two eyes are astonishingly similar, yet the fact that one sort belongs to a cephalopod mollusk with eight sucker-bearing arms, a saclike body,

and a beak and the other sort belongs to a species of primate means that they evolved along entirely different evolutionary lines. Those lines converged because the need to detect predators and prey at a distance is well met by a feature sensitive to electromagnetic radiation in the visible spectrum. In fact, the advantages of sight are so pronounced that eyes evolved independently in marine worms, mollusks, insects, and vertebrates—organisms whose common ancestor was sightless. Convergent evolution, then, is a powerful force, and it is known to operate at the cellular level. Some enzymes in familiar life are remarkably similar, yet have entirely different ancestries. If convergent evolution operates for weird life (and there is no obvious reason it should not), then forms of weird life and forms of familiar life, while radically different from each other when they first appeared, may have grown so alike over time as to be nearly indistinguishable.

A scientist verifying an organism as weird faces yet another challenge—this having to do with the nature of life's beginnings. Some biologists suspect that the transition from nonliving to living (that is, from complex chemistry to simple biology) was abrupt, akin to the phase transition of water as its temperature is lowered through the freezing point and it crystallizes—the moment at which its molecules suddenly snap to attention in rigid lattices. If one could define life as, for instance, having the ability to store and process information, one could establish a similar boundary. On one side would be complex chemistry that could not store and process information; on the other would be simple biology that could. The transition from one to the other, had anyone been around to witness it, would have been unmistakable. And if it happened a second time, even with slightly different results, it would have been just as unmistakable.

A well-defined transition would mean that scientists who discovered a candidate for weird life might trace its lineage to the moment of transition with some hope of success. But if, as others suspect, the transition was gradual—a long series of steps, some quite small, and no particular step of which anyone could say with certainty, "This is where chemistry ends and biology begins"—then scientists tracing the lineage of weird life would have no hope of identifying a point and moment of origin. Of course, neither would they have any hope of identifying a point and moment of familiar life's origin. To follow either line would be like following two rivers upstream and finding that both began in a single network of smaller streams and rivulets, and that these were fed in turn by moving groundwater. It would be impossible to identify precisely where either river began, and it would be impossible to say whether they arose from separate sources. In fact, it would be pointless even to try.

Again, we may be getting ahead of ourselves. Before we trace an organism's provenance and make a case for classifying it as weird, we need to find it. How then to begin? Davies and his colleagues recommend designing searches targeted around a particular type of shadow biosphere. If, for instance, we're looking for weird life in a shadow biosphere that is ecologically separate, we might look for that separation. Suppose we discover a community of extremophiles in 200°C water ringing a hydrothermal vent. If we found that the hotter water just inside the ring and nearer the vent was sterile, we might reason that the inside edge of the ring marks the upper temperature limit for these particular extremophiles. But suppose that even nearer the vent, where the water is hotter still, we found, after minding the gap, a second ring of living organisms, clearly separated from the first. We

would have some distance to go to prove it, but we would have reason to suspect that life in the second ring was weird.

If on-site identification proves difficult—and in these locales it often is—then Davies and his colleagues suggest we retrieve a sample of water, soil, or ice from a place too harsh even for extremophiles and, difficult as the prospect might be, try to culture any microbes present and wait for signs of life. Exactly what signs of life?

Steven Benner, another coauthor of the NRC report, has some ideas. Benner is a fellow at the Foundation for Applied Molecular Evolution, an organization whose rather audacious name is likely to prompt a few late-night discussions: Can we really apply evolution? Should we? Whatever the answers, the startling fact is that in the last twenty-five years, Benner and his colleagues have engineered several artificial biological components and systems. They have, for instance, synthesized a gene for an enzyme and built proteins with amino acids not used by natural proteins. Their work has practical benefits, having led, for example, to improvements in medical care for HIV patients. It might also be used in somewhat more arcane pursuits, like guiding searches for weird life. This because not only can Benner and his colleagues identify the parts of an organism that might be vulnerable to extreme conditions; they can also imagine substitutions for those parts. And because nature has had at least a 3.5-billion-year head start, so the thinking goes, anything Benner and company can imagine might already be out there somewhere.

For instance, the upper temperature limit for some hyperthermophiles is set by some of their amino acids, which denature at higher temperatures. Benner knows of another amino acid—2-methylamine acid—that folds in such a way that it can withstand those temperatures. If you are seeking weird life, you might retrieve a water sample from a place too hot even for hyperthermophiles, take it into the lab, and test for 2-methylamine acid. If you find it, you may also find weird life.

Alternatively, you might look for substitutions in the parts of DNA. Recall that if the DNA molecule is a flexible ladder whose ends have been given a few twists, then its long backbone (the two legs of the ladder) is made of sugar and phosphate molecules, and its rungs—all 3 billion of them—are made of chemicals called bases. There are four, and when the DNA molecule is intact, each is paired to its complement: adenine always with thymine, and guanine always with cytosine. This much is taught in any introduction to biology. What is seldom taught—and what might be of interest to seekers of a certain sort of weird life—is that the bases are what limit the pH levels tolerable for many extremophiles. Acidophiles can stand only so much acidity because the bases adenine and cytosine are relatively alkaline, and alkaliphiles can tolerate only so much alkalinity because thymine and guanine are relatively acidic. If weird-life DNA used different bases, it could withstand pH levels more extreme than those tolerated by known extremophiles.

ARSENIC

The weird life of an ecologically separate shadow biosphere might differ from familiar life in another fundamental way: its chemical composition. The fact that our bodies and the bodies of all life we know are made of a few simple chemical elements has been much used as a hard lesson in humility, a "to dust ye shall return" for secular types. But perhaps the better lesson is that the whole can be greater, much greater, than the sum of the

parts. The whole—here meaning incredibly complex structures like proteins and lipids—is ordered almost entirely from a spare menu of six chemical elements: carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus.*

"Phosphorus" means "light-bearing," and although we in the macroscopic world know it to be capable of fireworks, in the living cell it stores and transfers energy slowly and (one might say) carefully, as part of the chemical compound adenosine triphosphate, or ATP. It has other roles too, most notably in the phosphate (a molecule of one phosphorus atom and four oxygen atoms) that, along with sugar molecules, goes to make the spiraling backbone of the DNA molecule. What is interesting to weird-life research is that the roles of phosphorus could be performed as well by an element with a rather more sinister reputation: arsenic.

Arsenic is notorious as a poison and, perhaps as befits its part in many a murder mystery, it works on a biochemical level by stealth, mimicking phosphorus so well that it can gain entrance to a cell and make its way into metabolic pathways. Once inside, it turns ATP's careful distribution of energy into exchanges that are more explosive—and destructive. Nonetheless, like phosphorus, arsenic can bond molecules and store energy. If, some billion years ago, a set of complex, self-organizing prebiotic molecules was in need of an ingredient to do what phosphorus does for familiar life, and it happened to be in a place where phosphorus was rare but arsenic was plentiful, it might well have used arsenic for all its bonding and energy-storing needs—assuming,

* There are also trace elements, like iron and zinc, for which many organisms will make substitutions. Some mollusks, for instance, carry oxygen in their blood not with iron (the standard choice), but with copper.

of course, that it could develop means to cope with arsenic's instability.

It is worth noting that an organism using arsenic in the roles that familiar life gives to phosphorus would regard phosphorus as poisonous. If life had taken a different course, then we—or weird-life versions of us—might be suffering through summer stock productions of *Phosphorus and Old Lace*. But even given the course we know familiar life to have taken, it is possible that a second genesis of life chose arsenic, or that an early offshoot of familiar life substituted arsenic for phosphorus. It is also possible that in hydrothermal vents, hot springs, and closed-basin lakes—all places poor in phosphorus but rich in arsenic—it might still be hanging on.

In fact, this was the hypothesis that, in 2007, was put forth by a young postdoctoral researcher named Felisa Wolfe-Simon. She was already something of an iconoclast, having begun a career as a musician (trained as an oboist) but in time having earned a PhD from Rutgers in oceanography. In 2007 she was present in a workshop on weird life convened at Arizona State University by Davies, who was newly arrived there and laying groundwork for a research center that would address fundamental questions in science. Davies recalled, "We were kicking vague ideas around, but she had a very specific proposal and then went out and executed it."[15]

Wolfe-Simon's proposal had to do with Mono Lake, a closed basin in California's high desert some 20 kilometers across. Waters from the Sierra Nevada flow into the lake, and because they escape only by evaporation, the lake water is saturated with salts and minerals. Some of these precipitate into formations called "tufa towers" that, when the water level is low, rise above the surface like open-air stalagmites. Seen against the

stark beauty of the Sierra, the shoreline is decidedly unearthly. A good place, it would seem, to seek weird life, and—since the lake water has some of the highest concentrations of arsenic on Earth—especially weird life that likes arsenic.

In August 2009, Wolfe-Simon began working with Ron Oremland, a senior research scientist the US Geological Survey (USGS) and something of an expert in microbes that tolerate arsenic. They collected samples of water and sediment, and Wolfe-Simon carefully cultured bacteria from those samples, gradually and by stages diluting out the amount of phosphorus in their nutrients and increasing the amount of arsenic, with the intention of starving the phosphate users and nourishing the arsenic users, if there were any. By late fall of 2010, she and her research team had concluded that there was at least one arsenic user.

In a paper published in the journal *Science*, and at a NASA-sponsored news conference before a wall-sized image of Mono Lake at its otherworldly best, Wolfe-Simon reported that a bacterium of the family Halomonadaceae used arsenic in many important molecules, including DNA.[16] (She had named it GFAJ-1, an acronym for "Give Felisa a Job"—this an inside joke on anxieties concerning the temporary nature of her position with the USGS and hopes that the discovery might be a career maker.)

The claim was extraordinary, but the evidence for it—at least to many scientists—was less than compelling. They questioned whether the DNA had been sufficiently cleaned, suggested that water would have denatured any (alleged) arsenate-linked DNA, and claimed that remaining traces of phosphorus might have sustained the bacterium's growth. Norman Pace, an internationally respected microbiologist who, with Carl Woese, had done pioneering work on phylogeny and who, as another coauthor of the 2007 NRC report harbored no particular ill will for weird-life research in general, dismissed the work as unworthy of consideration, parsing the blame more or less evenly among "low levels of phosphate in the growth media, naïve investigators and bad reviewers."[17] Shelley Copely gave her own rather devastating take, opining, "This paper should not have been published."[18] There followed a days-long debate among scientists worldwide, much of it carried out in tweets and blog entries, over flaws in the experiment, the problems inherent in scientific peer review, and the general unreliability of NASA's public relations efforts, especially when they concerned microbiology. The paper's authors answered questions in a subsequent issue of *Science* but did not offer to revisit the study, and their critics were unappeased.

The episode became something of an embarrassment for all involved—NASA, whose Astrobiology Institute had supported the work of some of the paper's authors and had sponsored the news conference, the journal *Science* (whose peer reviewers had recommended publication), and of course, the authors themselves. Wolfe-Simon, far from backing away from her claims, has welcomed the critiques as part of the way good science is conducted. As of this writing, the one attempt by other researchers to reproduce Wolfe-Simon's results has failed.[19]

2-Methylamine acid and substitutions (like arsenic for phosphorus) in DNA are only two of the possibilities—informed guesses, as it were—of what to look for if we are seeking weird life in an ecologically separate biosphere. No doubt there are many others, most of them thus far unimagined.

Weird life that is ecologically integrated or biochemically integrated with our own biosphere would prefer less extreme conditions, and so might be more difficult to isolate, but there are ways. Davies suggests we might look for a difference more fundamental than any we've discussed thus far—that presented

by the "handedness" of molecules. You can't fit your right hand comfortably into a left-handed glove because the form of the glove is the form of the hand turned inside out, and vice versa. A biologist would say that the two gloves have different *chirality* (from the Greek for "hand"). Large molecules like amino acids and sugars also have chirality, and if they are to fit together to make still-larger molecules, like proteins and DNA, they must have the same chirality.

MIRROR, MIRROR

As it happens, every one of the amino acids used by proteins in familiar life is left-handed, and every sugar in DNA is right-handed. Things didn't have to be this way. Right-handed amino acids would have worked just as well, as long as all were right-handed, and left-handed sugars would have worked just as well, as long as all were left-handed. Things *are* this way because 3.5–3.8 billion years ago, some complex self-organizing prebiotic molecules needing an amino acid happened to use a left-handed one, and some needing a sugar happened to use a right-handed one. The first stitch set the pattern, and it has been followed ever since.

Suppose, however, that in any of the "second genesis" scenarios posited a few pages back, another set of complex self-organizing prebiotic molecules went right where the first had gone left, or went left where the first had gone right. The result might be a sort of weird life that is nearly identical to familiar life but, being made of molecules with mirror chirality, would be unable to interact with it biochemically. How might we find it? In fact, two scientists have already tried.

In 2006, acting on a suggestion from Davies, astrobiologist

Richard Hoover and microbiologist Elena Pikuta put out bait. They began with a standard culture medium, a sort of smorgasbord for microbes, and switched some of its nutrients for their mirror counterparts. Then they took extremophile microbes retrieved from Mono Lake and introduced them to the medium. The researchers expected that, if mirror microbes were living among the extremophile microbes, they would make their presence known by eating the mirror nutrients. Soon enough, something began to eat the nutrients, and after a moment of cautious excitement, Hoover and Pikuta identified that something not as a mirror microbe, but as a heretofore unknown bacterium of the familiar sort, possessed of an unusual ability to chemically alter the mirror nutrients so that it could better digest them. It was a bit of biochemical sleight of hand that Hoover and Pikuta now suspect is owed to certain enzymes. The finding came as a small disappointment, but it was only the first attempt of its kind, and the bacterium that they named *Anaerovirgula multivorans* (roughly, "little rod that will eat anything") was another reminder that a lot of nature was left to discover.[20]

There is another way that weird life might have escaped our attention: by being very, very small.

SIZE MATTERS

Every living organism known is made of cells. Although some cells are quite large (the Gargantua of celldom, *Thiomargarita namibiensis*, is the size of the period at the end of this sentence), most are best measured on the scale of nanometers—a nanometer being one-billionth of a meter. The lower limit for a cell's size seems to be set by *ribosomes*, the (relatively) large molecules of proteins and RNA that work inside all cells to link amino acids

and make new proteins. If they are to squeeze ribosomes inside themselves, cells must be a least a few hundred nanometers across. It is for this reason that most microbiologists think that smaller cells are impossible. Most microbiologists—but not all. Benner, for one, has suggested that cells might be much smaller if they made proteins not with ribosomes but with RNA.[21]

There have been at least three reports of very, very small things that—to their discoverers at least—seemed to be living or once living. In 1990, Robert Folk, an emeritus professor at the University of Texas at Austin, discovered in sedimentary rocks tiny structures that he took to be tiny fossils, the calcified remains of organisms a mere 30 nanometers across.[22] He has since found similar structures in other sediments and in meteorites. Some of his peers have been intrigued, and a few have pointed to Folk's findings as evidence that the tiny wormlike formations in the Martian meteorite ALH84001, while much smaller than bacteria, are not too small to have once been living. In 1996, Australian geologist Philippa Uwins was studying sandstone bore samples from a deep-ocean borehole off the coast of western Australia. She and her colleagues found tiny filaments that under an electron microscope looked like blobs in a lava lamp. By an ingenious method, Uwins was able to show that there was DNA inside the structures (not just on their surfaces)—evidence that they might be living, or at least might once have been living.[23] In 1988, Finnish biochemist Olavi Kajander was examining cells with an electron microscope and found within them tiny particles some 20 nanometers across.[24] Believing them to be living, he called them "nanobacteria." Of the three discoveries, Kajander's may be the strangest—and the most unsettling—because the particles are found in human tissue.

At present, the preponderance of evidence is that none of these findings is an organism, living or once living. In 2003 a research group concluded that what Folk had found were probably nothing more than by-products of bacteria with rather more typical dimensions.[25] Recent research suggests that Uwins's filaments are calcium carbonate and organic material that at some stage of development had encapsulated pieces of DNA.[26] And a National Institutes of Health (NIH) study published in 2000 threw serious doubt on Kajander's claims, which had already come under fire from several quarters. It should be said that Kajander himself continues to believe his "nanobacteria" are living, and his second thoughts are limited to his choice of nomenclature; he recently said that he probably should have given his findings a less provocative name, like (this is his phrase) "calcifying self-propagating nanoparticles."[27]

Most microbiologists have given these findings a wide berth. One reason is that the work done so far—Kajander's in particular—has generated controversies that give pause to scientists concerned for their careers and reputations. Nanoparticles, it seems, fall into a disciplinary no-man's-land between chemistry and biology. Microbiologist John Cisar, who led the NIH study that countered Kajander, noted, "I'm not saying there's nothing there. It's just that we were looking at it from a microbiologist's perspective. And when we didn't find any signs of life, we moved on."[28] These findings may represent a class of forms somewhere between nonlife and life, forms unknown to science. But whatever they are—weird life, unusual chemistry, or something in between—very small weird life remains a real possibility. As David McKay noted of Uwins's discovery (and it might easily apply to the others), "It's something that shows that we just do not understand the small end of the spectrum."[29]

As should by now be obvious, the big challenge facing seekers of weird life is that it could be weird in any number of ways, most of which we haven't thought of. It is for this reason that Davies has suggested that the strategy with the best chance of success is simply to broaden our gaze and look for things that are unexplained. One such thing, of particular interest to Carol Cleland, has been unexplained for a very long time.

DESERT VARNISH

In 1832, a young Charles Darwin was acting as assistant to the captain and unofficial naturalist aboard the HMS *Beagle*. As the ship was anchored off the coast of South America near San Salvador, Darwin explored the shore, where he was intrigued by rock outcroppings that glittered in the sunlight and seemed "burnished." He deduced that the rocks shone because of a coating of thin layers of metallic oxides, but he could not explain how it might have been made.[30]

Geologists have since found the same coating—now called "desert varnish"—in many locales. Although they are no more certain of its provenance than was Darwin, they have ideas. They also have two observations that give reason to suspect that this substance may be a product of biology. The first is that the thin layers of minerals and chemicals that desert varnish reveals in cross section resemble the layers found in "stromatolites." These are the mineral formations that in Shark Bay, Australia, look like half-submerged tortoise shells and in upstate New York look like fossilized cauliflower. Stromatolite layers are formed by generations of bacteria that, like a medieval city built and rebuilt on its own ruins, lived and died one atop another. The layering of desert varnish, so the thinking goes, might result from a similar biological process. The second observation is that many of the chemicals in desert varnish layers, most notably manganese and iron, are not in the rocks (like sandstone) that desert varnish typically varnishes, but are in fact produced by known organisms.

Even together, though, these observations are a long way from a clear-cut case for life. No laboratory microbiologist has been able to coax bacteria or algae to make desert varnish. And just as discouraging (to those who might wish it to be a product of organisms, that is), bacteria found in *in situ* desert varnish (the bacteria that might reasonably be expected to produce it) are of many varieties—too many, microbiologists think, to turn out the same product so consistently.

It is possible—and this is the prevailing view—that the stuff that intrigued Darwin and so many after him is the end result of some very complex chemistry. But no one has been able to reproduce that either. And so we have it: a natural phenomenon that exists in plain sight, and that after nearly two centuries of study remains a mystery. It is, so Cleland thinks, a fair candidate for weird life.

So far, we've learned of extremophiles that live at the outer boundaries of life as we know it. We've also learned of possibilities for life on Earth that, by subtle and not-so-subtle differences in their metabolism, might live beyond those boundaries. But we've been hugging the shoreline and reconnoitering a few nearby islands. Much of the remainder of this book will describe ideas of life that is much, much weirder. We'll venture into waters that are little charted, and are sometimes out of sight of the shoreline altogether. Before we do, though, we would be prudent to establish exactly where that shoreline is, and to take a good look back at it.

CHAPTER THREE

Defining Life

More than once in recent years, planetary scientists have been surprised to find water where they didn't expect to find it. On Mars, for example. The planet's atmosphere is so thin—so near a vacuum, in fact—that any liquid water on its surface would evaporate immediately, and even ice would be likely to sublime directly into water vapor. But since the mid-1970s, when NASA's twin *Viking* spacecraft imaged dry riverbeds and meandering tributary channels, it became apparent that once upon a time, perhaps 4 billion years ago, the surface of Mars had seen cataclysmic flooding. In the first decade of the twenty-first century, a small armada of spacecraft found more evidence of a watery Martian past—an outcropping that may be the shore of an ancient sea, and pack ice covered in volcanic ash. Most surprising were dry gullies and streambeds formed only a few thousand years ago, and evidence of a flash flood that happened even as the reconnaissance was under way. Since the 1970s, scientists had believed that when the planet lost most of its atmosphere, much of its water went with it. Now they know that some held