<u>THE SACRED DEPTH'S of NATURE,</u>

by Ursula Goodenough (1998)

Origin's of the Earth
Origin's of Life

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Origins of the Earth

INFINITIES AND INFINITESIMALS

Everything in our universe, including the Earth and its living creatures, obeys the laws of physics, laws that became manifest in the first moments of time. Much of what we know to be true about the physical universe, like the curvature of spacetime and the fact that electrons are both particles and waves, is very difficult to visualize, even for people who spend their lives thinking about such topics. Moreover, as physicists and mathemeticians probe ever more deeply, they present us with ever more mind-boggling concepts, like the idea that subatomic particles may in fact be minute, vibrating "superstrings" of space, that our four-dimensional universe may actually be ten-dimensional, that the observable universe may be much smaller than the true universe, and that there may be many other universes besides our own.

Fascinating as these known and speculative manifestations of physics may be, they prove not to be central to our story of life. Why? Because when Earth life was coming into being, some ten billion years after the universe had come into being, the laws of physics were a *given*. Life had no choice but to evolve in the context of quantum indeterminacy and gravitational fields and quarks held together by gluons. Therefore, while these facts underlie all of life, and constrain what can and cannot occur during biological evolution, we can describe how life works without referring to them, in much the same way that we can describe what a painting looks like without referring to the absorption spectra of its pigments.

What *is* central to the origin of Earth life is the history of the universe—the cosmic dynamics that yielded our star, our planet, and the atoms that form living things. We can tell the story sparingly, without pausing to define terminology, allowing the flow of events to suggest the enormous times and distances involved.

THE UNIVERSE STORY

The observable universe is about fifteen billion years old. In the beginning, everything that is now

that universe, including all of its space, was concentrated in a singularity, maybe the size of a pinhead, that was unimaginably hot (at least 100,000,000,000,000,000,000,000,000,000,000 degrees) and unimaginably dense. It all let loose during an event called the Big Bang, a misleading term in that there wasn't really an explosion. What happened was that the compacted space expanded very rapidly, carrying everything else along with it.

During the first three minutes of this expansion, all sorts of high-energy physics took place that yielded the current tally of subatomic particles in the universe, including protons, neutrons, and electrons. Some of the protons and neutrons fused to form helium ions, and random clumps developed in the expanding material so that it was not perfectly homogeneous. And then things started to settle down, with the space continuing to expand and cool until, after several hundred thousand years, temperatures were low enough that the protons and helium ions could acquire electron shells and become stable hydrogen and helium atoms. The expansion continued for another 15 billion years, yielding the present observable universe, 1,000,000,000,000,000,000,000,000 miles in diameter. Whether it will continue to expand or start to contract back again (the Big Crunch) is one of the many unknowns of cosmic evolution.

Because the early hydrogen and helium atoms were distributed inhomogeneously in the expanding space, close neighbors tended to move closer and then closer together, attracted by gravity. The result was that the universe became "lumpy," with vast gaseous clouds scattered here and there, occasionally colliding and merging with one another. These protogalaxies then differentiated, and continue to differentiate, into billions of galaxies, each giving rise to billions of stars.

A star starts out as a gaseous cloud, about three-quarters hydrogen and one-quarter helium. The atoms are brought together by gravitational attraction and, as they fall closer together, they speed up until the temperature is so high that they are stripped of their electrons and the hydrogen nuclei start to fuse, forming helium ions. These fusion reactions release heat, causing the gas to expand and counterbalancing its tendency to contract. As a result, the star stabilizes in temperature and size, often for billions of years, burning its hydrogen fuel.

Once the hydrogen begins to run out, the rate of nuclear fusion slows down and the gases no

longer expand as readily. As a result, the star begins to contract again, eventually becoming so dense and hot that its helium nuclei start to fuse together, forming larger nuclei like carbon, oxygen, calcium, and other "light" elements of the periodic table.

What happens next depends on the size of the star. A small star becomes unstable at this stage and puffs away its outer layers, seeding the galaxy with its newly minted light elements and leaving behind a remnant known as a white dwarf. A giant star keeps collapsing, getting hotter and hotter and forming heavier and heavier nuclei until it starts to make iron, which it can't burn. When a critical amount of iron accumulates, the core of the star is crushed by gravity into what is called a neutron star, and the shock waves generated by the crushing process cause a huge explosion in the star's outer layers—a supernova. Very heavy nuclei, including radioactive elements like uranium, are created during the supernova phase, and all the new kinds of nuclei are released into gaseous clouds where they cool, acquire electrons, and become atoms.

The gaseous clouds now go on to aggregate into second-generation stars that are more complex than their predecessors because they include some of the new kinds of atoms. The second-generation stars proceed to burn their hydrogen and collapse, forming more new elements in the process, and the released detritus then reaggregates into third-generation stars that are yet again more complex. Such birth-and-death stellar cycles are apparently destined to continue for billions of years into the future.

THE EARTH STORY

So now we can look at our own context. The Milky Way is a medium-sized galaxy, and the Sun, located in one of its spiral arms, is a second- or third-generation medium-sized star that formed from the atoms released by a nearby supernova. The Sun has existed for about 4.5 billion years and has enough hydrogen to burn for another 5 billion years or so. During its terminal phases it is expected to become so hot that the Earth will turn into a cinder.

While the Sun was forming, some of the surrounding material assembled into small aggregates that grew and collided and merged with one another and eventually stabilized as its orbiting planets, moons, and comets. Importantly, some of these aggregates, including what is now Earth, contained generous quantities of the atoms spewed out by supernovae: These include the iron and radioactive elements that form the Earth's broiling core, the sil-

icon that forms its crust, and the carbon, oxygen, nitrogen, and other elements that are essential for life. Moreover, comets colliding with the young Earth provisioned it with yet more atoms from distant supernovae, and also brought in a great deal of water in the form of ice. Gases trapped in the Earth's interior were released through fissures and volcanos and became trapped by gravity to form the early atmosphere, and the floating surface settled into large masses that drift and crash into one another in continuous geological activity, defining and redefining the continents and ocean basins. After about half a billion years of consolidation, the physical conditions on Earth became such that life could originate and continue.

Reflections

I've had a lot of trouble with the universe. It began soon after I was told about it in physics class. I was perhaps twenty, and I went on a camping trip, where I found myself in a sleeping bag looking up into the crisp Colorado night. Before I could look around for Orion and the Big Dipper, I was overwhelmed with terror. The panic became so acute that I had to roll over and bury my face in my pillow.

- All the stars that I see are part of but one galaxy.
- There are some 100 billion galaxies in the universe, with perhaps 100 billion stars in each one, occupying magnitudes of space that I cannot begin to imagine.
- Each star is dying, exploding, accreting, exploding again, splitting atoms and fusing nuclei under enormous temperatures and pressures.
- Our Sun too will die, frying the Earth to a crisp during its heat-death, spewing its bits and pieces out into the frigid nothingness of curved spacetime.

The night sky was ruined. I would never be able to look at it again. I wept into my pillow, the long slow tears of adolescent despair. And when I later encountered the famous quote from physicist Steven Weinberg—"The more the universe seems comprehensible, the more it seems pointless"—I wallowed in its poignant nihilism. A bleak emptiness overtook me whenever I thought about what was really going on out in the cosmos or deep in the atom. So I did my best not to think about such things.

But, since then, I have found a way to defeat the nihilism that lurks in the infinite and the infinitesimal. I have come to understand that I can deflect the apparent pointlessness of it all by realizing that I don't have to seek a point. In any of it. Instead, I can see it as the locus of Mystery.

- The Mystery of why there is anything at all, rather than nothing.
- The Mystery of where the laws of physics came from.
- The Mystery of why the universe seems so strange.

Mystery. Inherently pointless, inherently shrouded in its own absence of category. The clouds passing across the face of the deity in the stained-glass images of Heaven.

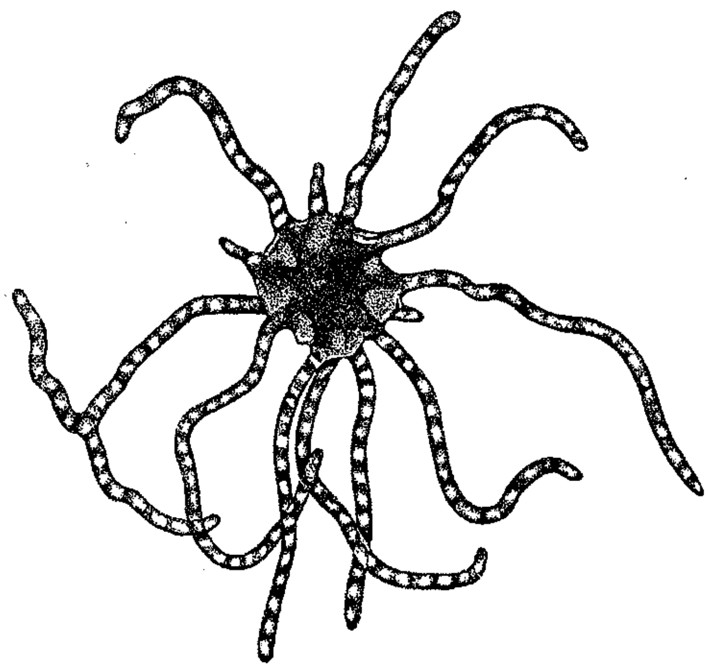
The word God is often used to name this mystery. A concept known as Deism proposes that God created the universe, orchestrating the Big Bang so as to author its laws, and then stepped back and allowed things to pursue their own course. For me, Deism doesn't work because I find I can only think of a creator in human terms, and the concept of a human-like creator of muons and neutrinos has no meaning for me. But more profoundly, Deism spoils my covenant with Mystery. To assign attributes to Mystery is to disenchant it, to take away its luminance.

I think of the ancients ascribing thunder and lightning to godly feuds, and I smile. The need for explanation pulsates in us all. Early humans, bursting with questions about Nature but with limited understanding of its dynamics, explained things in terms of supernatural persons and person-animals who delivered the droughts and floods and plagues, took the dead, and punished or forgave the wicked. Explanations taking the form of unseen persons were our only option when persons were the only things we felt we understood. Now, with our understanding of Nature arguably better than our understanding of persons, Nature can take its place as a strange but wondrous given.

The realization that I needn't have answers to the Big Questions, needn't seek answers to the Big Questions, has served as an epiphany. I lie on my back under the stars and the unseen galaxies and I let their enormity wash over me. I assimilate the vastness of the distances, the impermanence, the *fact* of it all. I go all the way out and then I go all the way down, to the fact of photons without mass and gauge bosons that become massless at high

temperatures. I take in the abstractions about forces and symmetries and they caress me, like Gregorian chants, the meaning of the words not mattering because the words are so haunting.

Mystery generates wonder, and wonder generates awe. The gasp can terrify or the gasp can emancipate. As I allow myself to experience cosmic and quantum Mystery, I join the saints and the visionaries in their experience of what they called the Divine, and I pulse with the spirit, if not the words, of my favorite hymn:



II

Origins of Life

Every religion has an account of the origins of life. Most familiar to Western traditions is Genesis 1, a spare, poetic account of the six days of creation. The Pueblo Indians tell of a primordial home beneath a lake where humans, gods, and animals lived together while the earth above was still soft and "unripe." The Kagaba Indians describe a female Supreme Deity: "the mother of our songs, the mother of all our seed, bore us in the beginning of things.... She is the mother of the thunder, the mother of the streams, the mother of trees and of all things." Certain Hindu teachings speak of the Brahmanda, the cosmic egg from which all creatures came forth. The Yaruro of Venezuala tell of the water serpent Puana who created the world, his brother Itciai, the jaguar, who created water, and their sister, Kuma, wife of the Sun, who made the Yaruro people.

These are wonderful stories that still work for us as stories, but we recognize their cultural origins and their contradictions with our present understanding of what happened. When we look to the scientific account of Nature for an origins story, we find a very different kind of poetry. It goes something like this.

THE ORIGINS OF CHEMISTRY

In the beginning there was high-energy physics, but during the cooling of the universe we encounter the origins of chemistry. Chemistry allows atoms to form bonds with one another and hence associate into molecules; it also allows smaller molecules to associate into larger molecules. Like everything else, chemistry is reducible to physics, but chemistry can only take place under certain conditions. There are three conditions that are important to our story.

- Chemistry requires the flow of energy, from a source to a sink. The Earth has two important sources of energy: the Sun, of course, and also its own molten core, pulsing with radioactivity, that helps heat up the oceans and the continents. The energy sink is, ultimately, the universe itself, most of which is only a few

degrees above absolute zero. As energy flows, chemistry can occur.
- Chemistry cannot occur when atoms are so hot that they fall apart into subatomic particles. It also cannot occur when everything is so cold that the atoms are all locked up together as solids, like a rock. When temperatures are such that atoms and molecules can coexist in their various forms—solids, liquids, and gases—this is a sign that the system is enjoying energy flow and that chemistry can proceed.
- Some atoms are more likely to engage in chemistry than others. Helium, for example, exists only as helium, whereas carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—the Big Six in living systems—are poised to form bonds with one another under conditions of energy flow: hydrogens readily combine with oxygens to form molecules of water; carbons readily combine with oxygens to form carbon dioxide.

THE BUILDING BLOCKS

Two kinds of chemistry were needed to get life going: the chemistry that generates the so-called building blocks of life—water, carbon dioxide, and small molecules like formaldehyde, methane, and hydrogen sulfide—and the chemistry that allows these to associate into yet larger assemblies called biochemicals.

The molecular building blocks for Earth life are thought to have been generated in two factories. The first are tiny specks of matter, about the size of talcum particles, called interstellar dust because they form huge clouds of matter between the stars, soaking up the elements released from stellar catastrophes. Since they are floating out in space, the specks are inherently cold, but as they are pulsed with radiation from nearby stars, they heat and cool, heat and cool, and this energy flow allows hundreds of different kinds of complex molecules to form on their surfaces. As comets and meteors passed through interstellar clouds and then crashed into Earth, they brought with them large cargos of such building blocks to be used by incipient life.

The second building-block factories are thought to have been deep-sea hydrothermal vents. Water seeped into fissures in the Earth's mantle, heated up, and then circulated back into the cold oceans, creating an energy flow that again allowed for the synthesis of many kinds of molecules, perhaps on the surfaces of clay or iron particles.

So small but complex building blocks are thought to have accumulated in the waters of the new Earth from the time it formed, about 4.5 billion years ago, creating what is often called the "primal soup." For our purposes, the most important ingredients of the soup were three kinds of small molecules called sugars, amino acids, and nucleotides, with the nucleotides being of two sorts—ribonucleotides and deoxyribonucleotides. These are important because they prove to be the starting materials for all forms of Earth life.

And then, about 4 billion years ago, the second kind of chemistry got underway: the formation of biomolecules from these primal-soup building blocks.

THE BIOMOLECULES

Here our story is obscured by a large fig leaf. We don't yet know the sequence of events that gave rise to the first biomolecules and then to the first cell, and perhaps we never will. But we know a great deal about the end result, about the biomolecules and cells that have come to inherit the Earth, and this allows us to work backwards, to propose plausible, if perhaps not correct, scenarios for the generation of life as we know it, scenarios that serve to focus our attention on what it entails to be alive. Such a story might go something like this.

Imagine a puddle of primal soup on the new Earth containing a large number of ribonucleotide building blocks. There are four different kinds of ribonucleotides, called A, C, G, and U, and they have the tendency, left to themselves for a very long time under conditions of energy flow, to form chemical bonds with one another and produce chains of random length, much like those chains of cut-out paper dolls connected together by their hands and feet. These chains are called RNA. Left to themselves, ribonucleotides will string together in random sequences: one RNA molecule might read ACAUGCACUCA; the next might read GAGCCUAGCACUACG; and so on. No life yet.

Now, the moment. One of these molecules—let's say UAGCACGUAAACGUC—happens to have the ability to copy itself. RNA molecules with such properties are found in odd creatures that are alive today. It isn't important to our story to consider how they work. The important part is the result: At the conclusion of such a self-replication event, the puddle comes to contain two copies of UAGCACGUAAACGUC. The two can now self-replicate to yield four copies, and then eight, and then sixteen, such that if we were to return to the puddle after 1,000 years and sample its RNA population, we would find that most of the molecules are now UAGCACGUAAACGUC. The puddle would presumably still contain the other RNA molecules that had formed by chance, but since these are not self-replicating, they would now represent a vanishingly small minority of the total RNA present.

The early copying process would be anything but perfect—meaning that a given progeny molecule might, for example, carry a G rather than a U at the first position and read GAGCACGUAAACGUC, a change known as a mutation. The mutation might cause the daughter molecule to lose its ability to self-replicate, in which case it would become a member of the small minority. But it might instead endow the molecule with the ability to self-replicate more rapidly, or more accurately, or both. Then, if we were to return to the puddle after another 1,000 years, we would expect to find that most of the molecules are now GAGCACGUAAACGUC. The UAGCACGUAAACGUC versions would still be present, and replicating away as best they can, but they would no longer be the most prevalent. There would have occurred what is called natural selection for the faster and more accurate replicator.

But now, a crisis. During the course of making all these RNA molecules, the puddle becomes depleted of its stock of ribonucleotide precursors—the A, C, G, and U building blocks that had provisioned the puddle. When the ribonucleotides run out, none of the RNA molecules, no matter how fast or accurate, can copy themselves. Everything stalls.

What happens next is that a mutant RNA molecule appears that is not only able to replicate itself, but is also able to carry the instructions for making more ribonucleotides, instructions encoded in units now known as genes. What this means, how it works, is the subject of later chapters. The important point here is that such an RNA molecule would have a huge advantage: It alone, of all the RNAs in the puddle, would be able to self-replicate because it alone could direct the synthesis of the ribonucleotides that are otherwise unavailable. It could, in effect, concoct its own primal soup, and natural selection would therefore favor its continuation.

Making more ribonucleotides and then allowing them to diffuse away into the puddle would not, however, be very efficient. A better strategy would be to surround the RNA in a membrane—a tiny bubble of lipid—such that when the ribonucleotides are synthesized, they stay inside the bubble, available for the next round of replication. Again postponing the question of how this works, we can say that further mutations generated an RNA molecule that carried the instructions—the genes—both for synthesizing ribonucleotides and enclosing them inside a membrane. At this point we are looking at the first cell: a membrane-enclosed self-replicating molecule capable of directing the synthesis of additional molecules, like membrane lipids and ribonucleotides, that make self-replication possible.

CELLS

There are good reasons to believe that cells with self-replicating RNA molecules were the first to inhabit the planet: The first world was apparently an "RNA world." But these cells have since vanished, or, rather, they have since evolved, into cells whose genes are encoded in DNA molecules, so we now live in a DNA world. DNA uses deoxyribonucleotides instead of ribonucleotides as precursors, and it is more stable than RNA, but the basic idea is otherwise the same: A long chain of deoxyribonucleotides carries genes whose molecular products make possible the replication of the chain.

Somewhere along the line, the genes encoded in RNA/DNA came to specify large molecules called proteins. Particularly important are proteins called enzymes, since they are responsible for getting the biochemistry inside the cell to proceed accurately and efficiently. How enzymes and other proteins work, and how DNA encodes their structure, will be considered in the next two chapters. Here we can stand back and take in the big picture.

The big picture is that a cell—and therefore life—must be able to construct itself, construct a cell, and then remember how to do it and pass the instructions on to daughter cells. We said that the initial building blocks in the primal soup were produced when pulses of energy from the sun or the Earth's interior made possible the chemistry of joining atoms together into molecules. We now say that this same kind of chemistry came to take place at moderate temperatures, and with increasing regularity and efficiency, inside tiny soap bubbles, with enzymes overseeing the biochemistry. The key role of DNA is to encode readable instructions for how to make the proteins and to pass these instructions along when it replicates.

Left out of this account is the critical question of how the chemistry is "driven"—that is, how energy is induced to flow through the cell at moderate temperatures and become trapped inside the biomolecules that are synthesized. Suffice it to say that along the way, cells first aquired the ability to extract energy from small molecules like hydrogen and hydrogen sulfide, and eventually developed the capacity to carry out photosynthesis—to capture energy from sunlight and transfer it into chemical bonds. Organisms that cannot do photosynthesis—like us—depend on the products of photosynthesis for survival: we ingest these products as food and then extract their energy in enzyme-mediated reactions collectively called metabolism.

PERSPECTIVE

For our origins story, then, two important points emerge. First, a system got thrown together, apparently quite by chance, that allows biomolecules to be sythesized by a sunlight-driven chemistry that is not at all left to chance. And, second, the instructions for constructing this system acquired the ability to be copied and inherited. That is, life emerged from nonlife. The stages that were traversed, the trials and errors, the near-extinctions, the struggles to recover, all these have been erased, supplanted by our intimate understanding of the ultimate winner, the first progenitor cell from whom all creatures flow.

Reflections

Life can be explained by its underlying chemistry, just as chemistry can be explained by its underlying physics. But the life that emerges from the underlying chemistry of biomolecules is something more than the collection of molecules. As we will see, once these molecules came to reside inside cells, they began to interact with one another to generate new processes, like motility and metabolism and perception, processes that are unique to living creatures, processes that have no counterpart at simpler levels. These new, life-specific functions are referred to as emergent functions.

The origin of life is but the first of many emergent functions we will encounter. A recent example is the emergence of self-awareness—our human ability to perceive the functioning of our own brains and call it "consciousness"—that in turn has given rise to the emergence of art and science and religious reflection. But we pause here to bear witness to the first discontinuity, the first biomolecules that were made again, and then again, and then again, from sets of RNA instructions. It was this that brought forth all the rest.

Emergence. Something more from nothing but. Life from nonlife, like wine from water, has

long been considered a miracle wrought by gods or God. Now it is seen to be the near-inevitable consequence of our thermal and chemical circumstances.

But what about those circumstances? Does not some theology flow from the fact that the universe was so "right," and our planet was so "right," that life became inevitable? A line of reasoning called the Anthropic Principle states that since the laws of physics are perfect for the emergence of chemistry, and chemistry is perfect for the emergence of life, that it all must have been Designed so as to yield life in general and human life in particular. Had any of the laws of physics been anything other than what they are, the universe would have been very different, and perhaps not possible at all, and life as we know it would not have evolved.

True enough. But of course, all these things could just as well have happened by chance since, had they occurred any other way, we wouldn't be sitting here wondering about them. The inherent circularity of Anthropic-Principle arguments leaves me, in the end, theologically unsatisfied.

And so I once again revert to my covenant with Mystery, and respond to the emergence of Life not with a search for its Design or Purpose but instead with outrageous celebration that it occurred at all. I take the concept of miracle and use it not as a manifestation of divine intervention but as the astonishing property of emergence. Life *does* generate something-more-from-nothing-but, over and over again, and each emergence, even though fully explainable by chemistry, is nonetheless miraculous.

The celebration of supernatural miracles has been central to traditional religions throughout the millennia. The religious naturalist is provisioned with tales of natural emergence that are, to my mind, far more magical than traditional miracles. Emergence is inherent in everything that is alive, allowing our yearning for supernatural miracles to be subsumed by our joy in the countless miracles that surround us.