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למרים שלי *For my Miriam*

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|ONE| INTRODUCTION

In the beginning, God created the heavens and the earth, and the earth was formless and void.
—Genesis 1:1–2

The puzzle breaks down as follows: every living thing we know of sprang from another living thing, yet we have reason to think that there was no life at all anywhere when the world first got going.[1] This observation implies that the first life there ever was grew from stuff that was not alive, and the question is whether this grand event occurred mysteriously, in a manner incomprehensible to the laws of physics and chemistry as we know them, or took place in a series of steps that we can understand. In other words, how did life begin? Scientists, curious observers of the natural world, and a great many other sorts of contemplative seekers struggling with the human condition may all agree on the importance of this question, yet much confusion and disagreement reigns about what kind of answer we are even looking for.

Some biophysicists might like to know which specific types of atoms collided with each other in order to form the first biomolecules, while others take for granted that something like this must have happened, and focus their inquiry instead on judging the likelihood of such an event under various conditions. For that matter, what even counts as life, and what doesn't? Was the early presence of life in the world a gray continuum through which things gradually progressed over time, or do we insist there must have been one moment when it burst decisively onto the scene? If the former, how precisely can we differentiate between something that is alive and something that isn't? If the latter, considering that life is good at doing an impressive number of things, which of them came into being first? Was it guaranteed to do so, in the same way that ice always melts in the warm sun, or must it have been sparked by a freak occurrence, one so rare that our best theory of how things transpired is no explanation at all? We understand something of why ice forms when water gets sufficiently cold, or why stars ignite when gravity is strong enough to squeeze hydrogen gas together, but it is strangely and marvelously more challenging to articulate the physical conditions in which nonliving matter is guaranteed to become alive. Like the skeptical onlooker at a magic show, many of us simply won't be satisfied until we get to see how the trick was done.

Tenacious scientific inquiry is not, however, the only reason people long so much to know something of how life began. A thoughtful human being—indeed, even a professional scientist willing to take an honest look in the mirror and examine his or her own sentiments carefully—may admit that the reason the question has such a command over us is that it expresses a shared yearning. The search for meaning and purpose begins with wondering where we came from and what we are part of, and seeking an account of how things began, partly because people use ideas about the past to decide how to act in the present and the future. If everything humans are made up of can be found in a pond or a chemistry set, then what really makes us different? Are humans simply animals, or something more? Does our existence express the intention of a Creator who made us in His image, or are we—and all other life—merely an exotic variety of frost condensed in the razor-thin layer between ground and sky? Can it be both? Once we start talking in these terms, the stakes of the argument could hardly be higher.

In this book, we will see that physical science does provide a new insight into when and how things that are not alive start to become more lifelike. Living things accomplish a variety of feats that, though not unique to life, are certainly distinctive of it. For example, they make copies of themselves, harvest and consume fuel, and accurately predict the surrounding environment. These processes are all part and parcel of what it is to be alive, and each of them can be studied systematically from the perspective of thermodynamics. Emphasizing recent progress in a rapidly growing offshoot of thermodynamics known as nonequilibrium statistical mechanics, this text will build up all the concepts needed to construct a clear argument for when and how the physical properties of inanimate matter might first give rise to the kinds of activities that life is particularly good at. The key point will be to realize that, just as living things have specialized properties determined by their genes that they have inherited from their ancestors, so, too, do collections of physically interacting particles have specialized properties that come from the past shapes into which they've been assembled. By continually getting pushed and knocked around by patterns presented in the environment, matter can undergo a continual exploration of the space of possible shapes whose rhythm and form become matched to those patterns in ways that look an awful lot like living.

If all we aimed to do here were to make new physical sense of life's distinctiveness, that would be plenty. And yet, even more so than most other scientific topics, this one surely demands a broader conversation. Whether because one needs to grapple mightily with the simple, definitional question of what is alive and what is not, or because arguments about the exceptionality, value, and purpose of life make up a large part of what people have disagreed and fought about throughout the ages, it seems thoroughly necessary to put our examination of the boundary between life and non-life in a suitably rich philosophical context. There might be more than one way of doing this well, in principle, but this is where my own deeply felt personal commitments come to bear. The way I know how to be most effective and accurate when talking about "big questions" of the human condition is to ground my understanding in interpretations of the Hebrew Bible. At the beginning of conceiving this book, I therefore set to pondering whether the Bible had anything cogent to say in reaction to the physics I planned to write about.

What I have been amazed to discover is that the Bible is *particularly* interested in the question of how and why matter might cross from being lifeless to alive, and that it features this subject at the center of one of its most central narrative moments. As a result, the biblical text turns out to provide an unexpectedly detailed conceptual roadmap for the scientific journey we are about to undertake, one that is useful not only for making physical insights comprehensible to the intuitions of everyday experience, but ultimately also in navigating the broader consequences for how we think about the human condition. Moreover, in what feels to me a very pleasing side effect of this whole endeavor, we are going to articulate a way of relating to the Hebrew Bible that combines with and enriches what science can teach us, instead of seeming to be incompatible. It is usually taken for granted that the Bible comprehends little or nothing of what modern science knows about the natural world; it has even been asserted that progress in scientific understanding of where life comes from directly undercuts the credibility and authority of biblical scripture as a path to true knowledge.[2] This book so happens to demonstrate the profound falsity of that assertion, but not by injecting more argumentation into an already bloated debate. Instead, engaging with the Bible presents us with a delightful opportunity to prove the point by example, for not only does its text seem to be aware of the concepts needed to think about the emergence of lifelikeness in a physical material, it even provides a poetic summary of them using imagery that makes them more relatable and broadly comprehensible.

For me, in this regard, there is a very satisfying harmony here between the demands of a personal commitment and what simply does the best job when trying to teach about the physicochemical ideas contained in this book. An account of how life might emerge from "dumb, blind" mechanical processes unavoidably will look to some rhetoricians like a last stake in the heart of the Bible's account of creation—not only this, it also risks casting the whole intricate web of interwoven human lives as a wholly material process that is devoid of any moral meaning. I therefore have a firm intention to lay out the discussion in such a way that the relevant commentary provided by Hebrew scripture never actually appears at loggerheads with the science in the way that some mistakenly perceive. At the same time, the way the Bible treats the subject of how matter comes to life turns out to be wondrously useful as an explanatory tool, because scripture addresses itself to the unenhanced perspective of a human being observing and assaying the world with little beyond his or her five senses. Ideas that are born in the mathematical realm of statistical thermodynamics can often be translated into more everyday parlance, but doing so usually requires reference to tangible examples in that everyday world. In quite deliberate fashion, the Book of Exodus provides a whole drawer-full of these examples, and if I do my job right here, then including them in our discussion is going to make the meaning of the physical theory clearer to a greater number of readers.

Moses is a lone shepherd in the desert tending sheep when he encounters a shrub wreathed in marvelous fire, a living thing that burns brightly without being consumed. The God who reveals Himself in that moment speaks to Moses of his nation's ancestry and the promise of their redemption from slavery, but He also provides three signs for Moses to bring to the Hebrews in Egypt. The first sign is a staff that turns into a serpent. The second is a "snowy" growth on his skin. The last is a mixture of river water and dirt that turns into blood.

Each of these signs can be read as a comment about the border between life and non-life. The staff is a lifeless object that surprisingly transforms into a living creature. The snowy skin is an anomaly in the boundary between the body of a man (who is alive) and his surroundings (which are not), and the reference to snowflakes evokes the idea of an ever-branching edge that is impossible to trace and thereby fully define. And, of course, the creation of blood—the liquid essence of life—from more basic, formless ingredients completes the portrait. Viewed in these terms, this passage from Exodus hammers home the question of where life comes from and how we can distinguish it from the inanimate material background from which it might have emerged.

It is easiest to think of the miraculous signs given to Moses as a bunch of parlor tricks. Indeed, the text expects this, for when Moses and his brother Aaron show their mud-blood and transforming reptilian stick to Pharaoh, the magicians of the Egyptian court are able to produce the same dazzling effects using their own spells. Superficially, the passage therefore invites those of us fascinated by life's emergence to compare ourselves to the audience at a magic show. Looking more closely, however, we will discover that these signs also serve as a surprisingly cogent and detailed guide for explaining emergent lifelikeness in the language of physics. The titles for the chapters of this book—2, *Staff and Snake*; 3, *Snow and Dust*; 4, *River and Blood*; 5, *Mountain and Sword*; 6, *Flame and Tree*; 7, *Wind and Breath*; and 8, *Voice and Word*—all come from the biblical text, and I have paired each one with an accompanying epigraph that highlights the title theme. These pairings will allow us to ruminate on the biology and physics of life from a new perspective. My goal in setting things down in this way is to let this biblical lexicon provide a rich organizing framework for the separate ideas in the natural sciences that must be woven together into a complete account of the origins of living things. By tracing this path, we will not only get a glimpse of how lifelikeness "gets going" in material terms, but also, by the end, begin to appreciate how the Bible seeks to express and comment on such a perspective, so that our reaction to it stays grounded in a full appreciation of what the lives we are living have the potential to mean.

Before plunging ahead, however, it will be well worth our while to state a bit more concretely what kind of answer to the question of where life came from one could possibly hope to put forward in what follows. The most straightforward notion of what such a success could look like would be the perhaps childlike hope that we could one day make a movie of exactly whichever storied puddle it was where certain special chemical reactions first happened, and (crucially!), that we would be able to prove, using data gathered in the present, that the movie was a faithful model of what took place in the past.[3] There is more than one reason why that kind of approach is a fantasy, but the most fundamental must certainly be that we do not have—and cannot ever have—any evidence in the present day of exactly what happened on Earth however many billions of years back. Much the same way that both crime scenes and archaeological digs are ruined irreparably for forensic analysis if all the clues are allowed to be trampled, tampered with, and rearranged at random, so, too, must the precursors of the earliest life have gotten scrambled—only much, much more severely. DNA, RNA, and proteins are all macromolecules central to how life works at the subcellular level, and all of them fall to pieces in water on the time scale of millions of years or less.[4] No one is foolish enough to try to comb the beach sand at Coney Island trying to reconstruct what a child's castle might have looked like for a few hours one summer day a hundred years ago, and reconstructing the molecular origins of life as we know it by trying to detect its leftover debris is a fool's errand.

There is, however, a different kind of approach one can take to explaining where something came from. The underlying premise of asking about the origins of life is that there is something here that needs an explanation, and it is helpful to try to be precise about what that is. When we go hiking in the mountains and notice a bunch of rocks at the bottom of a ravine, we are not provoked to ask how they got there; the same goes for pine cones we step on when walking under a pine tree. Of course, when I see a pine cone in a place in which I find it perfectly normal to observe one, I do not actually know with certainty what the whole history of that particular cone is; maybe someone actually put it there under the tree by hand before I arrived. Still, it does not seem out of place, because there is a perfectly ordinary, observable, and reproducible way to get pine cones to accumulate under pine trees. They fall there all the time as part of the normal seasonal ebb and flow of things.

This is the sense in which life seems to demand an explanation of the sort we might have a hope of constructing. We do not typically (or really ever) see living things spring from inert, inanimate matter, and so it seems abnormal to us to imagine it happening as an explanation for the life we see. Moreover, it is clear to our intuition that this is not merely an issue of our being unable to wait long enough. Of course, some processes that seem rare and improbable on one time scale (like a bolt of lightning on a particular mountain peak) become near-certainties if we just wait a hundred or a million times longer. Still, when we look at life, in all of its intricacy, it is apparent that the simplest of examples of it that we know are so complexly assembled that you would have to wait the ages of countless universes before seeing all these parts slapped together from one random fluke. The exact amount of time it all would have had to take obviously must have been the consequence of little details in this or that chemical process that might take a hundred years under one set of conditions or a million years under another. Nonetheless, the account we really hunger for—the only kind of account that could provide an answer that is both testable and (at least to some degree) satisfying—is for the first assembly of life to be conceived of as a process that has been decomposed into steps that can be theoretically understood and experimentally implemented and observed—in other words, into steps that each look to us like pine cones falling off trees.

I aim to showcase the beginnings of this sort of an understanding within these pages. I do not know, and never expect to know, exactly which molecules did what or when a long, long time ago. What I *do* want to propose is that there is a set of ideas, based on a branch of physics called nonequilibrium thermodynamics, that is starting to show us how to break the stepwise process of life's emergence into comprehensible increments. Once we recognize that life, through the lens of physics, is an omnibus of specific but different phenomena with precise physical definitions, we can study the emergence of these phenomena more in parallel, as little, limited successes in lifelike self-organization. The more these pieces of the puzzle can be separately implemented, poked, and tweaked in a laboratory, the more we can start to relate to them as banal, tangible bits of the places and timetables we inhabit.

Central to this discussion will be an idea I have called dissipative adaptation, which essentially is a fancy way of saying that when matter gets knocked around by the patterns in its surroundings, it ends up getting stuck in shapes that look specially suited to respond to those patterns. We are going to have to lay out a number of different observations about physics and biology in order to build this idea up a bit more rigorously, but one of the gratifying things about this kind of science is that it stays very much in contact with the examples of messy complexity that we encounter in everyday life. What that means is that, by the time we reach our conclusion, you may be in the position to test much of what is being claimed here against the evidence of your own significant experience, whether that be watching sleet slide down a windshield in cold rain or observing how salt and pepper grains dance together in a pan of heated oil.

|TWO| STAFF AND SNAKE

So he threw it to the ground, and it became a serpent.
—Exodus 4:3

There is just something obviously reasonable about the following notion: if all life is built from atoms that obey precise equations we know—which seems to be true—then the existence of life might just be some downstream consequence of these laws that we haven't yet gotten around to calculating. This is essentially a physicist's way of thinking, and to its credit, it has already done a great deal to help us understand how living things work. Thanks to pioneers like Max Delbrück, who crossed over from physics to biology in the middle of the twentieth century, the influence of quantitative analyses from the physical sciences helped to give rise to mechanistic, molecular approaches in cell biology and biochemistry that led to many revolutionary discoveries. Imaging techniques such as X-ray crystallography, nuclear magnetic resonance, and super-resolution microscopy have provided a vivid portrait of the DNA, proteins, and other structures smaller than a single cell that make life tick on a molecular scale.[1] Moreover, by cracking the genetic code, we have become able to harness the machinery of living cells to do our bidding by assembling new macromolecules of our own devising. As we have gained an ever more accurate picture of how life's tiniest and simplest building blocks fit together to form the whole, it has become increasingly tempting to imagine that biology's toughest puzzles may only be solved once we figure out how to tackle them on physics' terms.

But approaching the subject of life with this attitude will fail us, for at least two reasons. The first reason we might call the boils. Indeed, it often seems people expect that a good enough physical theory could become the new gold standard for saying what is alive and what is not. What I will argue here, however, is that this approach fails to acknowledge that our own role in giving names to the phenomena of the world precedes our ability to say with any clarity what it means to even call something *alive*. A physicist who wants to devise theories of how living things behave or emerge has to start by making intuitive choices about how to translate the characteristics of the examples of life we know into a physical language. After one has done so, it quickly becomes clear that the boundary between what is alive and what is not is something that already got drawn at the outset, through a different way of talking than physics provides. The proper goal for a physicist's account of things should therefore be to find a way of describing that boundary in precise physical terms, so that we can get new insight into how matter might be gotten to move from one side of the borderline to the other.

To some degree, a hopeful inclination toward reductionism is expressed in the very asking of the question of where life comes from. We look at a living organism and cannot help but wonder whether such breathtaking success in form and function could simply be the result of a bunch of more basic pieces bouncing off of each other like simple and predictable billiard balls. Is there something more in the machine other than all its dumbly vibrating parts? If there isn't, shouldn't that mean we can eventually understand how the whole thing fits together? Put another way, wouldn't any proposed explanation for the emergence of life have to break it all down into a series of rationalized steps, where each next one follows sensibly and predictably from the last? If so, how is that not the same thing as saying we want to reduce life to a choreographed performance directed by a simple, calculable set of known physical rules?

As I've said, it must be granted that physicists have already identified some rules that prove to make highly accurate predictions in systems that once seemed hopelessly and mysteriously complicated. Thanks to the ideas of people like Kepler and Newton, the motion of heavenly bodies is now an open book, and our ability to compute where these bright lights in the