THE FIFTH MIRACLE

The Search for the Origin and Meaning of Life

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In memory of Keith Runcorn

PREFACE

IN AUGUST 1996, the world was electrified by news that an ancient meteorite may contain evidence for life on Mars. President Clinton himself conveyed the story to the public and a startled scientific community. The momentous implications of the discovery, if such it was, were expressed in appropriate superlatives. This memorable event marked one of the few occasions when a scientific result had a direct impact on the public. Yet the plaudits and the banter glossed over the true significance of the findings.

For several years, scientists have been dramatically rethinking their ideas about the origin of life. The textbooks say that life began in some tepid pool on the Earth's surface, billions of years ago. Increasingly, however, the evidence points to a very different scenario. It now appears that the first terrestrial organisms lived deep underground, entombed within geothermally heated rocks in pressure-cooker conditions. Only later did they migrate to the surface. Astonishingly, descendants of these primordial microbes are still there, kilometers beneath our feet.

Until a few years ago, nobody suspected that life could exist in such a harsh environment, but once it was accepted that organisms can flourish beneath the Earth's surface, an even more exotic possibility presented itself. Perhaps microbes also lurk in the rocks beneath the surface of Mars? The discovery of a Martian rock containing possible fossilized bacteria was a major boost to this theory. But that was not all. Scientists were quick to spot a fascinating consequence. It could be that life actually began on Mars and then traveled to Earth in a meteorite.

The feverish excitement surrounding the Martian meteorite concealed deep divisions among the experts over the interpretation of the evidence. If confirmed, it could mean either that life has started twice in the solar system, or, alternatively, that it has spread from one planet to another. Exciting though it would be to discover that organisms can leap from planet to planet, the ultimate origin of life would still be left as an unresolved enigma if the latter explanation were correct.

How, precisely, did life begin? What physical and chemical processes can transform nonliving matter into a living organism? This much tougher problem remains one of the great scientific challenges of our age. It is currently being tackled by an army of chemists, biologists, astronomers, physicists, and mathematicians. On the basis of their research, many of them fervently conclude that the laws of nature are, to put it bluntly, rigged in favor of life. They expect that life will form wherever conditions permit—not just on Mars, but throughout the universe; and, more provocatively, in a test tube. If they are right, it will mean that life is part of the natural order of things, and that we are not alone.

Belief that life is written into the laws of nature carries a faint echo of a bygone religious age, of a universe designed for habitation by living creatures. Many scientists are scornful of such notions, insisting that the origin of life was a freak accident of chemistry, unique to Earth, and that the subsequent emergence of complex organisms, including conscious beings, is likewise purely the chance outcome of a gigantic cosmic lottery. At stake in this debate is the very place of mankind in the cosmos—who we are and where we fit into the grand scheme.

Astronomers think that the universe began in a big bang between ten and twenty billion years ago. Its explosive birth was accompanied by a flash of intense heat. During the first split second, the basic physical forces and fundamental particles of matter emerged. By the time that one second had elapsed, the essential materials of the cosmos had already formed. Space was everywhere filled with a soup of subatomic particles—protons, neutrons, and electrons—bathed in radiation at a temperature of ten billion degrees.

By present standards the universe at that epoch was astonishingly featureless. The cosmic material was spread through space with almost perfect uniformity. The temperature was the same everywhere. Matter, stripped down to its basic constituents by the fierce heat, was in a state of extraordinary simplicity. A hypothetical observer would have had no inkling from this unpromising state that the universe was primed with awesome potentialities. No clue would betray that, several billion years on, trillions of blazing stars would organize themselves into billions of spiral galaxies, that planets and crystals, clouds and oceans, mountains and glaciers would arise, that trees and bacteria and elephants and fish would inhabit one of these planets, and that this world would ring to the sound of human laughter. None of these things could be foretold.

As the universe expanded from its uniform primeval state, it cooled. And with lower temperatures came more possibilities. Matter was able to aggregate into vast amorphous structures—the seeds of today's galaxies. Atoms began to form, paving the way for chemistry and the formation of solid physical objects.

Many wonderful phenomena have emerged in the universe since that time: monstrous black holes weighing as much as a billion suns that eat stars and spew forth jets of gas; neutron stars spinning a thousand times a second, their material crushed to a billion tons per cubic centimeter; subatomic particles so elusive that they could penetrate light-years of solid lead; ghostly gravitational waves whose fleeting passage leaves no discernible imprint at all. Yet, amazing though these things may be, the phenomenon of life is more remarkable than all of them put together. It didn't bring about any sudden and dramatic alterations on the cosmic scene. In fact, if life on Earth is anything to go by, the changes it has wrought have been extremely gradual. Nevertheless, once life was initiated, the universe would never be the same. Slowly but surely it has transformed Planet Earth. And by offering a route to consciousness, intelligence, and technology, it has the potential to change the universe.

This book is about the origin of life, or biogenesis. I should state at the outset that the subject is not my professional field. I trained as a theoretical physicist. I have, however, always had a fascination for the problem of biogenesis and the related question of whether or not we are alone in the universe. I can trace my interest in these matters back to my days as a student studying physics at University College, London, in the 1960s. Like many of my friends, I read Fred Hoyle's famous science-fiction novel *The Black Cloud,* about the arrival in the solar system of a large cloud of gas from interstellar space.[1] Such clouds are well known to astronomers, but Hoyle's intriguing idea was to suppose that they could be alive. Now, this was a poser. How can a cloud be alive? I puzzled over it at length. Surely gas clouds just obey the laws of physics? How could they exhibit autonomous behavior, have thoughts, make choices? But, then, it occurred to me, all living organisms supposedly obey the laws of physics. Hoyle's brilliance was in using the example of a cloud to draw out that paradox in a stark manner.

The Black Cloud left me baffled and vaguely disturbed. What exactly, I wondered, *is* life? And how did it get started? Might there be something funny going on inside living organisms? Just at this time, my Ph.D. supervisor gave me (as an exercise in light relief) a curious paper by the highly respected physicist Eugene Wigner. The paper purported to prove that a physical system could not make a transition from a nonliving to a living state without contravening the laws of quantum physics.[2] Aha! So Wigner at least thought that something funny must have gone on when life started.

Shortly afterwards, my supervisor passed me another paper related to biology, this time by the astrophysicist Brandon Carter. It addressed an important and interesting problem concerning life, but one that dodged the need to worry about what it actually is or how it began. Carter asked the question, what properties must the physical universe have in order for life of any sort to exist at all? Suppose that by magic you could change the laws of nature or the initial conditions of the big bang. How far could you alter the basic laws or the structure of the universe, and still permit life? To take a simple example, life as we know it demands certain chemical elements, especially carbon. But few carbon atoms were made in the big bang; most were manufactured inside stars. Fred Hoyle had already noticed that the successful production of carbon in stars is actually a rather touch-and-go affair. It depends delicately on the properties of nuclear forces. Tinker with the basic laws of nuclear physics, and the universe would have little or no carbon and probably no life. Carter's ideas became known as "the anthropic principle," and suggested, audaciously, that the very existence of life is a dicey affair, a consequence of some happy coincidences in the underlying mathematical structure of the universe.

Thought-provoking though Carter's paper was, it still left the secret of life unexplained. Shortly after reading it, I got a job as a research fellow at The Institute of Theoretical Astronomy in Cambridge, where Fred Hoyle was the director and Brandon Carter a fellow researcher. During that time, I chanced across a little book by the physicist Erwin Schrödinger that seemed to address my very problem. Entitled *What Is Life?,* it set out to explain why biological organisms seem so mysterious from the point of view of physics.[3] I later discovered that this book had been immensely influential twenty years before, in the early days of the subject of molecular biology.

Unfortunately, Schrödinger's book raised more questions for me than it answered, and I consigned the problem of biogenesis to my mental "too-hard" basket. However, Carter gave me a revised copy of his paper on the anthropic principle (which he never published[4]) and, together with Bill Saslaw, another researcher at the Institute, I dabbled around with Carter's ideas. We even tried to get a meeting with Francis Crick, who at that time worked at the Medical Research Council Laboratory in Cambridge. But Crick was too busy, and Carter seemed to have pretty well sewn up the subject of the anthropic principle, so my interest in matters biological began to wane.

It was rekindled only many years later, in the early 1980s. Martin Rees (now Sir Martin Rees, the Astronomer Royal) helped organize a conference in Cambridge called "From Matter to Life." Rees, together with fellow astronomer Bernard Carr, had revitalized the subject of the anthropic principle in a famous paper published in *Nature* in 1979.[5] The conference brought together physicists and astronomers such as Brandon Carter, Freeman Dyson, and Tommy Gold, biologists like Lewis Wolpert and Sydney Brenner, mathematician John Conway, and biogenesis supremos Manfred Eigen and Graham Cairns-Smith. The agenda focused on how life began, and though no firm conclusions were drawn, the meeting served to point up the key scientific and conceptual problems. I resumed thinking about the mystery of life. Over the following decade or so, I found myself being influenced once again by the ideas of Hoyle, and also by those of Dyson and Gold. Hoyle, with collaborator Chandra Wickramasinghe, daringly suggested that maybe life did not originate on Earth at all, but was brought here by comets. Dyson also speculated on the origin of life, and let his imagination run free about the future and ultimate fate of technological civilizations. Gold had a theory that large quantities of hydrocarbons lie trapped under the ground; when a search was made to test his hypothesis, new subterranean life forms were discovered. All these developments helped shape my thinking on the subject.

Another person who greatly influenced my interest in biogenesis was the late Keith Runcorn, my former colleague at the University of Newcastle upon Tyne. Runcorn was a geophysicist whose interests extended well beyond Earth into the solar system. Although geophysics was far from my own area of expertise, I would often sit in on Keith's seminars and conferences. The fiftieth meeting of the Meteoritical Society, held in Newcastle in 1987, was especially memorable, for it was there that I first learned about the Martian meteorites.

The final piece of the jigsaw came in the early 1990s, by which time I had moved to Australia to work at The University of Adelaide. There I became interested in the work of Duncan Steel, an expert on asteroid and cometary impacts with the planets. It was Steel who introduced me to the fact that material could be ejected from the planets by cosmic collisions, an idea that laid the foundations for my theory about micro-organisms traveling between Mars and Earth.

When I set out to write this book, I was convinced that science was close to wrapping up the mystery of life's origin. The dramatic evidence for microbes living deep underground promised to provide the "missing link" between the prebiotic world of biochemical soups and the first primitive cells. And it is true that many scientists working in this field confidently believe that the major problems of biogenesis have largely been solved. Several recent books convey the confident message that life's origin is not really so mysterious after all.[6] However, I think they are wrong. Having spent a year or two researching the field, I am now of the opinion that there remains a huge gulf in our understanding. To be sure, we have a good idea of the where and the when of life's origin, but we are a very long way from comprehending the how.

This gulf in understanding is not merely ignorance about certain technical details, it is a major conceptual lacuna. I am not suggesting that life's origin was a supernatural event, only that we are missing something very fundamental about the whole business. If it is the case, as so many experts and commentators suggest, that life is bound to arise given the right conditions, then something truly amazing is happening in the universe, something with profound philosophical ramifications. My personal belief, for what it is worth, is that a fully satisfactory theory of the origin of life demands some radically new ideas.

Many investigators feel uneasy about stating in public that the origin of life is a mystery, even though behind closed doors they freely admit that they are baffled. There seem to be two reasons for their unease. First, they feel it opens the door to religious fundamentalists and their god-of-the-gaps pseudo-explanations.[7] Second, they worry that a frank admission of ignorance will undermine funding, especially for the search for life in space. The view seems to be that governments are more likely to spend money seeking extraterrestrial life if scientists are already convinced that it is out there.

In my opinion, this attitude is totally misguided. Scientists do their disciplines no credit by making exaggerated claims merely for public consumption. More important, ignorance provides a much better motivation for experiment than certainty. It is important to seek life on other worlds, and to try and synthesize it in the laboratory, precisely *because* we are so uncertain of how it came to be. For this reason, I strongly support NASA's new Astrobiology program. If I am right that biogenesis hints at something profoundly new and amazing, then searching other worlds may enable us to catch this remarkable transition in the act. Astronomers consider the outer planets like Saturn and Jupiter and their moons to be gigantic prebiotic laboratories, where the steps that led to life on Earth have been frozen in time, poised partway between the realm of complex chemistry and the realm of true biology.

In the case of Mars, it seems likely that the line between nonlife and life will have been crossed, and that, at some stage in the past, life flourished on the red planet. In fact, for reasons I shall explain in this book, I believe that past life on Mars was a virtual certainty. I also think there is a good chance of finding life there today, if you know where to look.

Solving the mystery of biogenesis is not just another problem on a long list of must-do scientific projects. Like the origin of the universe and the origin of consciousness, it represents something altogether deeper, because it tests the very foundations of our science and our world-view. A discovery that promises to change the very principles on which our understanding of the physical world is built deserves to be treated as an urgent priority. The mystery of life's origin has puzzled philosophers, theologians, and scientists for over two and a half millennia. During the next decade, we have a golden opportunity to make some major advances in this field. That scientists are currently stumped makes this opportunity all the more exciting and compelling.

I believe that we will not solve the problem of biogenesis without first having a deep understanding of the nature of life. What, exactly, is it? Life is so extraordinary in its properties that it qualifies for the description of an alternative state of matter. I begin the book by seeking a definition of life—a notoriously difficult problem. Most textbooks focus on the chemistry of life: which molecules do what inside the cell. Obviously, life is a chemical phenomenon, but its distinctiveness lies not in the chemistry as such. The secret of life comes instead from its informational properties; a living organism is a complex information-processing system.

Complexity and information can be illuminated by the subject of thermodynamics, a branch of science that links physics, chemistry, and computation. For decades there has been a suspicion that life is so amazing that it must somehow circumvent the laws of thermodynamics. In particular, the second law of thermodynamics, arguably the most fundamental of all the laws of nature, describes a trend of decay and degeneration that life clearly bucks. I have devoted chapter 2 to an extensive discussion of the second law of thermodynamics, for it provides the context for what I regard as the ultimate problem of biogenesis: namely, where biological information came from. Whatever remarkable chemistry may have occurred on the primeval Earth or some other planet, life was sparked not by a molecular maelstrom as such, but—somehow!—by *the organization of information.* It is a theme I develop further in chapters 3, 4, and 5, where I describe the various competing theories of primordial soups and other scenarios for turning chemistry into life, plus some of the attempts to create life in the laboratory. I also give a brief review of the fossil evidence for the earliest life forms. Some of the introductory sections on Darwinism and basic molecular biology may be familiar to the reader, and could be skipped. However, I have tried to present the orthodox ideas with a novel slant.

If I am right that the key to biogenesis lies, not with chemistry, but with the formation of a particular logical and informational architecture, then the crucial step involved the creation of an information-processing system, employing software control. In chapter 4, I argue that this step was closely associated with the appearance of the genetic code. Bringing some of the language and concepts of computation to the problem, I have endeavored to throw light on the highly novel form of complexity that is found in the genes of living organisms. The peculiarity of biological complexity make genes seem almost like impossible objects—yet they must have formed somehow. I have come to the conclusion that no familiar law of nature could produce such a structure from incoherent chemicals with the inevitability that some scientists assert. If life does form easily, and is common throughout the universe, then new physical principles must be at work. It is a theme that I take up in the final chapter, where I have tried to spell out the immense philosophical ramifications that follow if the universe teems with life—as many people seem to believe is the case. Though I have no doubt that the origin of life was not in fact a miracle, I do believe that we live in a bio-friendly universe of a stunningly ingenious character.

Most of the latter half of the book is devoted to a radical new theory for the origin of life. Since the time of Darwin, there have been only two broad theories of biogenesis. The first is that life began by chemical self-assembly in a watery medium somewhere on the Earth's surface—Darwin himself wrote of a "warm little pond."[8] The other is that life came to Earth from space in the form of already viable microbes—the so-called panspermia hypothesis. In the latter scenario, the ultimate origin of life is left as a mystery. In recent years, however, the evidence has increasingly suggested to me a third alternative: that life began *inside* the Earth. Not in the far interior, of course, but several kilometers down in the solid crust, probably beneath the seabed, where geothermal activity creates cauldronlike conditions. The extreme heat and chemical potency of the subsurface zone, especially near volcanic vents, would instantly kill most known organisms. However, such an environment was ideal for biogenesis, and scientists have discovered bizarre microbes still living in these scalding locations today, at temperatures well above the boiling point of water. These superbugs are described in chapter 7, where I argue that they are living fossils left over from the dawn of life.

I believe that very similar superbugs once lived beneath the surface of Mars, and may well exist there today, far underground, for reasons explained in chapter 8. Furthermore, I am convinced that micro-organisms have traveled between Earth and Mars inside rocks blasted from these planets by the impacts of giant meteorites. A large part of chapter 8 is devoted to the contentious issue of Martian meteorites, especially the famous ALH84001, which NASA scientists have claimed contains fossil Martian microbes. The near-certainty of planetary cross-contamination, which seems to have been overlooked by most scientists and commentators involved in the recent life-on-Mars debate, makes the ultimate origin of life problematic. Did it start on Earth, Mars, or both independently? Or somewhere else entirely? I discuss the importance of astronomy to biogenesis in chapter 6, and review the evidence for revived panspermia theories in chapter 9.

In preparing this book, I have benefited considerably from detailed discussions with many distinguished colleagues. Some I have already mentioned. Special thanks must go to Susan Barns, Robert Hannaford, John Parkes, Steven Rose, Mike Russell, Duncan Steel, and Malcolm Walter, all of whom kindly read and commented on early drafts of the manuscript. Other people who have given me valuable assistance during the writing phase are Diane Addie, David Blair, Julian Brown, Roger Buick, Julian Chela-Flores, George Coyne, Helena Cronin, Robert Crotty, Susan Davies, Reza Ghadiri, Monica Grady, Gerry Joyce, Stuart Kauffman, Bernd-Olaf Küppers, Clifford Matthews, Chris McKay, Jay Melosh, Curt Mileikowsky, Martin Redfern, Martin Rees, Everett Shock, Lee Smolin, Karl Stetter, Roger Summons, Ruediger Vaas, Frances Westall, and Ian Wright.

Finally, I should like to add a few words about the title of this book. It derives from the biblical account in the book of Genesis, which describes how God made the world in a series of specific steps. Verse 11 of the first chapter states, “Let the land produce vegetation.” This is the first mention of life, and it seems to be the fifth miracle. The preceding four miracles are the creation of the universe, the creation of light, the creation of the firmament, and the creation of dry land. Biblical scholars tell me that this enumeration is a misreading of Genesis, because the opening line, “In the beginning God created the heavens and the earth,” is not in fact the description of a miraculous act, but a statement of the overall agenda that is itemized in the subsequent verses. Nevertheless, I have stuck to the fifth miracle. In using this title, I am not suggesting that the origin of life actually was a miracle. I refer those readers interested in the theological aspects of this topic to my earlier books *The Mind of God*[9] and *Are We Alone?*[10]

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CHAPTER 1

The Meaning of Life

IMAGINE BOARDING A TIME MACHINE and being transported back four billion years. What will await you when you step out? No green hills or sandy shores. No white cliffs or dense forests. The young planet bears little resemblance to its equable appearance today. Indeed, the name "Earth" seems a serious misnomer. "Ocean" would suit better, for the whole world is almost completely submerged beneath a deep layer of hot water. No continents divide the scalding seas. Here and there the peak of a mighty volcano thrusts above the surface of the water and belches forth immense clouds of noxious gas. The atmosphere is crushingly dense and completely unbreathable. The sky, when free of cloud, is lit by a sun as deadly as a nuclear reactor, drenching the planet in ultraviolet rays. At night, bright meteors flash across the heavens. Occasionally a large meteorite penetrates the atmosphere and plunges into the ocean, raising gigantic tsunamis, kilometers high, which crash around the globe.

The seabed at the base of the global ocean is unlike the familiar rock of today. A Hadean furnace lies just beneath, still aglow with primeval heat. In places the thin crust ruptures, producing vast fissures from which molten lava erupts to invade the ocean depths. The seawater, prevented from boiling by the enormous pressure of the overlying layers, infuses the labyrinthine fumaroles, creating a tumultuous chemical imbroglio that reaches deep into the heaving crust. And somewhere in those torrid depths, in the dark recesses of the seabed, something extraordinary is happening, something that is destined to reshape the planet and, eventually perhaps, the universe. Life is being born.

The foregoing description is undeniably a speculative reconstruction. It is but one of many possible scenarios offered by scientists for the origin of life, but increasingly it seems the most plausible. Twenty years ago, it would have been heresy to suggest that life on Earth began in the torrid volcanic depths, far from air and sunlight. Yet the evidence is mounting that our oldest ancestors did not crawl out of the slime so much as ascend from the sulfurous underworld. It may even be that we surface dwellers are something of an aberration, an eccentric adaptation that arose only because of the rather special circumstances of Earth. If there is life elsewhere in the universe, it may well be almost entirely subterranean, and only rarely manifested on a planetary surface.

Although there is now a measure of agreement that Earth's earliest bioforms were deep-living microbes, opinion remains divided over whether life actually began way down in the Earth's crust, or merely took up residence there early on. For, in spite of spectacular progress over the past few decades in molecular biology and biochemistry, scientists still don't know for sure how life began. The outline of a theory is available, but we are a long way from having a blow-by-blow account of the processes that transformed matter into life. Even the exact location of the incubator remains a frustrating mystery. It could be that life didn't originate on Earth at all; it may have come here from space.

The challenge facing scientists struggling to explain the origin of life is the need to piece together a narrative of events that happened billions of years ago and have left little or no trace. The task is a daunting one. Fortunately, during the last few years some remarkable discoveries have been made about the likely nature of Earth's most primitive organisms. There have also been great strides in laboratory procedures, and a growing understanding of conditions in the early solar system. The recent revival of interest in the possibility of life on Mars has also served to broaden the thinking about the conditions necessary for life. Together, these developments have elevated the subject from a speculative backwater of science to a mainstream research project.

The problem of how and where life began is one of the great outstanding mysteries of science. But it is more than that. The story of life's origin has ramifications for philosophy and even religion. Answers to such profound questions as whether we are the only sentient beings in the universe, whether life is the product of random accident or deeply rooted law, and whether there may be some sort of ultimate meaning to our existence, hinge on what science can reveal about the formation of life.

In a subject supercharged with such significance, lack of agreement is unsurprising. Some scientists regard life as a bizarre chemical freak, unique in the universe, whereas others insist that it is the expected product of felicitous natural laws. If the magnificent edifice of life is the consequence of a random and purely incidental quirk of fate, as the French biologist Jacques Monod claimed, we must surely find common cause with his bleak atheism, so eloquently expressed in these words: "The ancient covenant is in pieces: man at last knows that he is alone in the unfeeling immensity of the universe, out of which he has emerged only by chance. Neither his destiny nor his duty have been written down."[1] But if it transpires that life emerged more or less on cue as part of the deep lawfulness of the cosmos—if it is scripted into the great cosmic drama in a basic manner—it hints at a universe with a purpose. In short, the origin of life is the key to the meaning of life.

In the coming chapters I shall carefully examine the latest scientific evidence in an attempt to confront these contentious philosophical issues. Just how bio-friendly is the universe? Is life unique to Planet Earth? How can something as complex as even the simplest organism be the product of straightforward physical processes?

Life's mysterious origin

> *The origin of life appears . . . to be almost a miracle, so many are the conditions which would have had to be satisfied to get it going.*
>
> FRANCIS CRICK[2]

According to the Australian Aborigines of the Kimberley, in the Creation Time of Lalai, Wallanganda, the sovereign of the galaxy and maker of the Earth, let fresh water fall from space upon Wunggud, the giant Earth Snake. Wunggud, whose very body is made of the primeval material, was coiled into a ball of jellylike substance, *ngallalla yawun.* On receiving the invigorating water, Wunggud stirred. She formed depressions in the ground, *garagi,* to collect the water. Then she made the rain, and initiated the rhythmic processes of life: the seasons, the reproductive cycles, menstruation. Her creative powers shaped the landscape and brought forth all creatures and growing things, over which she still holds dominion.[3]

All cultures have their creation myths, some more colorful than others. For centuries, Western civilization looked to the Bible for enlightenment on the subject. The biblical text seems disappointingly bland when set beside the Australian story: God created life in more or less its present form *ab initio*, as the fifth miracle.

Not far from the Kimberley—across the Great Sandy Desert, in the mountains of the Pilbara—lie the oldest known fossils on Earth. These extraordinary remains form part of the scientific account of creation. Science takes as its starting point the assumption that life wasn't made by a god or a supernatural being: it happened unaided and spontaneously, as a natural process.

Over the past two centuries, scientists have painstakingly pieced together the history of life. The fossil record shows clearly that ancient life was very different from extant life. Generally speaking, the farther back in time you go, the simpler were the living things that inhabited Earth. The great proliferation of complex life forms occurred only within the last billion years. The oldest well-documented true animal fossils, also to be found in Australia (in the Flinders Ranges, north of Adelaide), are dated at 560 million years. Known as Ediacara, they include creatures resembling jellyfish. Shortly after this epoch, about 545 million years ago, there began a veritable explosion of species, culminating in the colonization of the land by large plants and animals. But before about one billion years ago, life was restricted to single-celled organisms. This record of complexification and diversification is broadly explained by Darwin's theory of evolution, which paints a picture of species continually branching and rebranching to form more and more distinct lineages. Conversely, in the past these lineages converge. The evidence strongly affirms that all life on Earth descended via this branching process from a common ancestor. That is, every person, every animal and plant, every invisible bacterium can be traced back to the same tiny microbe that lived billions of years ago, and thence back to the first living thing.[4] What remains to be explained—what stands out as the central unsolved puzzle in the scientific account of life—is how the first microbe came to exist.

Peering into life's innermost workings serves only to deepen the mystery. The living cell is the most complex system of its size known to mankind. Its host of specialized molecules, many found nowhere else but within living material, are themselves already enormously complex. They execute a dance of exquisite fidelity, orchestrated with breathtaking precision. Vastly more elaborate than the most complicated ballet, the dance of life encompasses countless molecular performers in synergetic coordination. Yet this is a dance with no sign of a choreographer. No intelligent supervisor, no mystic force, no conscious controlling agency swings the molecules into place at the right time, chooses the appropriate players, closes the links, uncouples the partners, moves them on. The dance of life is spontaneous, self-sustaining, and self-creating.

How did something so immensely complicated, so finessed, so exquisitely clever, come into being all on its own? How can mindless molecules, capable only of pushing and pulling their immediate neighbors, cooperate to form and sustain something as ingenious as a living organism?

Solving this riddle is an exercise in many disciplines—biology foremost, but chemistry, geology, astronomy, mathematics, computing, and physics contribute too. It is also an exercise in history. Few scientists believe that life began in a single monumental leap. No physical process abruptly "breathed life" into inert matter. There must have been a long and complicated transitional stage between the nonliving and the first truly living thing, an extended chronology of events unlikely to be preordained in its myriad details. A law of nature could not alone explain how life began, because no conceivable law would compel a legion of atoms to follow precisely a prescribed sequence of assemblage. So, although complying with the laws of nature, the actual route to life must have owed much to chance and circumstance—or contingency, as philosophers call it. Because of this, and because of our ignorance about the conditions that prevailed in the remote past, we will never know exactly which particular sequence of events produced the first life form.

The mystery of biogenesis runs far deeper than ignorance over details, however. There is also a profound conceptual problem concerning the very nature of life. I have on my desk one of those lamps, popular in the 1960s, containing two differently colored fluids that don't mix. Blobs of one fluid slowly rise and fall through the other. People often comment that the behavior of the blobs is "lifelike." The lamp is not alone in this respect. Many inanimate systems have lifelike qualities—flickering flames, snowflakes, cloud patterns, swirling eddies in a river. What is it that distinguishes genuine living organisms from merely lifelike systems? It is not simply a matter of degree; there is a real difference between the nature of the living and the merely lifelike. If a chicken lays an egg, it is a fair bet that the hatched fledgling will also be a chicken; but try predicting the precise shape of the next snowflake. The crucial difference is that the chicken is made according to specific genetic instructions, whereas lamp blobs, snowflakes, and eddies form willy-nilly. There is no gene for a snowflake. Biological complexity is *instructed* complexity or, to use modern parlance, it is information-based complexity. In the coming chapters I shall argue that it is not enough to know how life's immense structural complexity arose; we must also account for the origin of biological information. As we shall see, scientists are still very far from solving this fundamental conceptual puzzle. Some people rejoice in such ignorance, imagining that it leaves room for a miraculous creation. However, it is the job of science to solve mysteries without recourse to divine intervention. Just because scientists are still uncertain how life began does not mean life cannot have had a natural origin.

How does one go about assembling a scientific account of the genesis of life? At first sight the task seems hopeless. The traditional method of seeking rock fossils offers few clues. Most of the delicate prebiotic molecules that gave rise to life will long ago have been eradicated. The best we can hope for is some degraded chemical residue of the ancestral organisms from which familiar cellular life evolved.

If we had to rely on rock fossils alone, the task of understanding the origin and early evolution of life would indeed be formidable. Fortunately, there is another line of evidence altogether. It too stretches back into the dim and distant past, but it exists right here and now, inside extant life forms. Biologists are convinced that relics of ancient organisms live on in the structures and biochemical processes of their descendants—including human beings. By studying how the modern cell operates, we can glimpse remnants of ancestral life at work—a peculiar molecule here, an odd chemical reaction there—in the same way that out-of-place coins, rusty tools, or suspicious mounds of earth alert the archaeologist. So, amid the intricate processes going on inside modern organisms, traces of primeval life survive, forming a bridge with our distant past. Analyzing these obscure traces, scientists have made a start on reconstructing the physical and chemical pathways that may have brought the first living cell into existence.

Even with such biochemical clues, the task of reconstruction would still be largely guesswork were it not for the recent discovery of certain "living fossils"—microbes that inhabit weird and extreme environments. These so-called superbugs are being intensively investigated, and look set to revolutionize microbiology. It could be that we are glimpsing in these offbeat microbes something close to the primitive organisms that spawned all life on Earth. More clues may come from the search for life on Mars and other planets, and the study of comets and meteorites. By piecing together all these strands of evidence, we may yet be able to deduce, in broad outline at least, the way in which life first emerged in the universe.

What is life?

Before we tackle the problem of its origin, it is important to have a clear idea of what life is. Fifty years ago, many scientists were convinced the mystery of life was about to be solved. Biologists recognized that the key lay among the molecular components within the cell. Physicists had by then made impressive strides elucidating the structure of matter at the atomic level, and it looked as if they would soon clear up the problem of life too. The agenda was set by the publication of Erwin Schrödinger's book *What Is Life?* in 1944. Living organisms, it seemed at the time, would turn out to be nothing more than elaborate machines with microscopic parts that could be studied using the techniques of experimental physics. Careful investigation lent support to this view. The living cell is indeed crammed with miniature machines. All it required was an assembly manual and the problem would be solved. Today, however, the picture of the cell as nothing but a very complicated mechanism seems rather naïve. To be sure, molecular biology has scored some dazzling successes, but scientists still can't quite put their finger on *exactly* what it is that separates a living organism from other types of physical objects. Though treating organisms as mechanisms has undoubtedly proved very fruitful, it is important not to be mesmerized by its simplistic charm. Mechanistic explanation is an important part of understanding life, not the whole story.

Let me give a striking example of where the problem lies. Imagine throwing a dead bird and a live bird into the air. The dead bird will land with a thud, predictably, a few meters away. The live bird may well end up perched improbably on a television aerial across town, on the branch of a tree, on a rooftop, in a hedgerow, or in a nest. It would be hard to guess in advance exactly where.

As a physicist, I am used to thinking of matter as passive, inert and clodlike, responding only when coerced by external forces—as when the dead bird plunges to the ground under the tug of gravity. But living creatures literally have a life of their own. It is as if they contain some inner spark that gives them autonomy, so that they can (within limits) do as they please. Even bacteria do their own thing in a restricted way. Does this inner freedom, this spontaneity, imply that life defies the laws of physics, or do organisms merely harness those laws for their own ends? If so, how? And where do such "ends" come from in a world apparently ruled by blind and purposeless forces?

This property of autonomy, or self-determination, seems to touch on the most enigmatic aspect that distinguishes living from nonliving things, but it is hard to know where it comes from. What physical properties of living organisms confer autonomy upon them? Nobody knows.

Autonomy is one important characteristic of life. But there are many others, including the following:

Reproduction. A living organism should be able to reproduce. However, some nonliving things, like crystals and bush fires, can reproduce, whereas viruses, which many people would regard as living, are unable to multiply on their own. Mules are certainly living, even though, being sterile, they cannot reproduce. A successful offspring is more than a mere facsimile of the original; it also includes *a copy of the replication apparatus.* To propagate their genes beyond the next generation, organisms must replicate the means of replication, as well as replicating the genes themselves.

Metabolism. To be considered as properly alive, an organism has to *do* something. Every organism processes chemicals through complicated sequences of reactions, and as a result garners energy to enable it to carry out tasks, such as movement and reproduction. This chemical processing and energy liberation is called metabolism. However, metabolism cannot be equated with life. Some micro-organisms can become completely dormant for long periods of time, with their vital functions shut down. We would be reluctant to pronounce them dead if it is possible for them to be revived.

Nutrition. This is closely related to metabolism. Seal up a living organism in a box for long enough and in due course it will cease to function and eventually die. Crucial to life is a continual throughput of matter and energy. For example, animals eat, plants photosynthesize. But a flow of matter and energy alone fails to capture the real business of life. The Great Red Spot of Jupiter is a fluid vortex sustained by a flow of matter and energy. Nobody suggests it is alive. In addition, it is not energy as such that life needs, but something like useful, or free, energy. More on this later.

Complexity. All known forms of life are amazingly complex. Even single-celled organisms such as bacteria are veritable beehives of activity involving millions of components. In part, it is this complexity that guarantees the unpredictability of organisms. On the other hand, a hurricane and a galaxy are also very complex. Hurricanes are notoriously unpredictable. Many nonliving physical systems are what scientists call chaotic—their behavior is too complicated to predict, and may even be random.

Organization. Maybe it is not complexity *per se* that is significant, but *organized* complexity. The components of an organism must cooperate with each other or the organism will cease to function as a coherent unity. For example, a set of arteries and veins are not much use without a heart to pump blood through them. A pair of legs will offer little locomotive advantage if each leg moves on its own, without reference to the other. Even within individual cells the degree of cooperation is astonishing. Molecules don't simply career about haphazardly, but show all the hallmarks of a factory assembly line, with a high degree of specialization, a division of labor, and a command-and-control structure.

Growth and development. Individual organisms grow and ecosystems tend to spread (if conditions are right). But many nonliving things grow too (crystals, rust, clouds). A subtler yet altogether more significant property of living things, treated as a class, is development. The remarkable story of life on Earth is one of gradual evolutionary adaptation, as a result of variety and novelty. Variation is the key. It is replication combined with variation that leads to Darwinian evolution. We might consider turning the problem upside down and say: if it evolves in the way Darwin described, it lives.

Information content. In recent years scientists have stressed the analogy between living organisms and computers. Crucially, the information needed to replicate an organism is passed on in the genes from parent to offspring. So life is information technology writ small. But, again, information as such is not enough. Though there is information aplenty in the positions of the fallen leaves in a forest, it doesn't *mean* anything. To qualify for the description of living, information must be meaningful to the system that receives it: there must be a "context." In other words, the information must be *specified.* But where does this context itself come from, and how does a meaningful specification arise spontaneously in nature?

Hardware/software entanglement. As we shall see, all life of the sort found on Earth stems from a deal struck between two very different classes of molecules: nucleic acids and proteins. These groups complement each other in terms of their chemical properties, but the contract goes much deeper than that, to the very heart of what is meant by life. Nucleic acids store life's software; the proteins are the real workers and constitute the hardware. The two chemical realms can support each other only because there is a highly specific and refined communication channel between them mediated by a code, the so-called genetic code. This code, and the communication channel—both advanced products of evolution—have the effect of entangling the hardware and software aspects of life in a baffling and almost paradoxical manner.

Permanence and change. A further paradox of life concerns the strange conjunction of permanence and change. This ancient puzzle is sometimes referred to by philosophers as the problem of being versus becoming. The job of genes is to replicate, to conserve the genetic message. But without variation, adaptation is impossible and the genes will eventually get snuffed out: adapt or die is the Darwinian imperative. How do conservation and change coexist in one system? This contradiction lies at the heart of biology. Life flourishes on Earth because of the creative tension that exists between these conflicting demands; we still do not fully understand how the game is played out.

It will be obvious that there is no easy answer to Schrödinger's question: what is life? No simple defining quality distinguishes the living from the nonliving. Perhaps that is just as well, because science presents the natural world as a unity. Anything that drives a wedge between the domains of the living and the nonliving risks biasing us towards the belief that life is magical or mystical, rather than something entirely natural. It is a mistake to seek a sharp dividing line between living and nonliving systems. You can't strip away the frills and identify some irreducible core of life, such as a particular molecule. There is no such thing as a living molecule, only a system of molecular processes that, taken collectively, may be considered alive.

I can summarize this list of qualities by stating that, broadly speaking, life seems to involve two crucial factors: metabolism and reproduction. We can see that in our own lives. The most basic things that human beings do are breathe, eat, drink, excrete, and have sex. The first four activities are necessary for metabolism; the last is necessary for reproduction. It is doubtful that we would consider a population of entities that have metabolism but no reproduction, or reproduction without metabolism, to be living in the full sense of the term.

The life force and other discredited notions

Given the elusive character of life, it is not surprising that some people have resorted to mystical interpretations. Perhaps organisms are infused with some sort of essence or soul that brings them alive? The belief that life requires an extra ingredient over and above ordinary matter obeying normal physical laws is known as vitalism. It is a beguiling idea with a long history. The Greek philosopher Aristotle proposed that a special quality which he called the life force, or psyche, bestowed upon living organisms their remarkable properties, especially that of autonomy or self-movement. Aristotle's psyche was different from the later Christian idea of the soul as a special and separate entity. Indeed, in Aristotle's scheme, everything in the universe was considered to possess intrinsic